Research Article

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The effects of bruising and temperature on enzyme activity and textural qualities of tomato juice

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Abstract

BACKGROUND: During harvest and transportation, processing tomatoes are exposed to elevated temperatures, compression and vibration in the harvester and truck, making them prone to bruising. The objective of this study was to determine how bruising and exposure to high temperatures affect pectin methylesterase (PME) activation and the textural quality of tomato juice.

RESULTS: Tomatoes were both hand and mechanically harvested using current harvest practices. Mechanically harvested fruits were significantly softer, had greater PME activity and greater juice consistency than hand harvested fruits. In a controlled bruising study, whole tomatoes were exposed to various compressive forces at 21 or 40 °C and held for 0 or 4 h. Greater bruising force and higher temperature resulted in a decrease in firmness and an increase in PME activity. Consistency of tomato juice improved when tomatoes were exposed to 40 °C. Tomatoes subjected to a temperature range from 21 to 65 °C had activated PME at 40 °C and increased activity as temperature increased. Consistency increased at 35 °C but decreased with increasing temperature.

CONCLUSION: Tomatoes harvested using current mechanical techniques are likely to be less firm and have increased PME activity; however, increased consistency of processed juice is observed. Tomatoes harvested at higher temperatures are also likely to have better consistency when processed.

Keywords: tomato; processing; pectin methylesterase; Bostwick; bruising; consistency

INTRODUCTION

Processing tomatoes (*Lycopersicon esculentum* Mill.) are used for production of tomato paste, sauces, canned tomato products and other value-added products. In 2008 the state of California accounted for over 90% of the United States production of processing tomatoes and 35% of the worldwide production.[1] Extensive measures have been taken to optimize the harvesting technology of tomatoes;[2] however, a relatively small amount of research has been conducted on how these technological developments affect the fruit itself and how these effects translate into the quality of the final product.

From the time that the tomato plant is removed from the ground, the fruit is exposed to an environment where it is prone to damage. Harvesters contain a system of conveyer belts and devices designed to remove non-fruit material, which during harvest may subject the fruit to falls, bounces, vibration and compression.[2] Once harvested, tomatoes are transported to the processing facility in the gondolas of trucks, each containing a maximum of 25 000 lb (11 340 kg), where they can experience acceleration changes, vibration, heat and compression from other fruit in the gondolas. By the time the fruit reaches the processing facility, it is likely that it has sustained some degree of physical damage.

Pectin methylesterase (PME) is an enzyme which is present during tomato maturation and has been shown to increase in activity during ripening.[3] PME catalyzes the demethylation of galacturonic acid residues in cell wall pectin and is activated when a tomato is bruised.[4,5] The action of PME allows for further pectin degradation by polygalacturonase (PG),[6] resulting in a loss in firmness. However, the action of PME also increases the binding sites for divalent cations, which form cross bridges between sections of pectin polymers. These cross bridges have been shown to increase desirable textural attributes of tomatoes and tomato products.[7–9] The state of pectin, whether it is degraded by PG or reinforced by cross bridges, is an important factor in the consistency of processed products. York *et al.*[10] have demonstrated that the solubility state of pectin is directly correlated with consistency measurements. How PME activation by bruising alters pectic structures during harvest and transportation, and how these alterations translate into textural changes in tomato products, requires further investigation.

Damage to fruit has been replicated in laboratory settings using various methods: dropping fruit from determined heights,[11] dropping a weight onto a fruit,[12] using a pendulum to impart a force[5] and using compressive plates.[13] Use of a pendulum to invoke PME

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and PG activity found that there was no significant activation of either enzyme after a 3 h hold time;[5] however the effect of temperature was not explored. In another study the effects of bruising on the textural quality of tomato juice were examined by bouncing tomatoes down a Plexiglas chute to simulate bruising experienced during harvesting.[10] The study found no trend between damage and consistency changes; however, when a consistency change was observed, soluble solids content was higher as well.

It is speculated by the tomato processing community that the more extensively bruised a tomato is when it reaches the processor, the less desirable the quality of the finished product. Previous studies have evaluated the effects of bruising on fruits intended for the fresh market, which are stored for days, weeks or months.[14,15] Extended storage allows for damage due to bruising to develop and other tissue degradation to occur, but very few studies have been reported on the effects of bruising within the short timeframe typical of harvest and transportation[5] and even fewer on how that translates into processed product quality. The objectives of this study were (1) to determine the effects of current harvest and transportation technology on the enzymatic activity and textural quality of the final processed product, (2) using controlled studies, to evaluate the effects of various applied forces, temperatures and hold times that a tomato may experience during harvest and transportation on the enzymatic activity and textural quality of the final processed product and (3) to measure the temperature dependence of PME activity over a range of temperatures and evaluate how that activity translates into textural changes.

EXPERIMENTAL

Field study

Raw materials

Commercial fields of two processing tomato cultivars, Heinz 8004 and Sun 6366, were identified in Woodland, Lemoore and Gilroy, CA during the 2012 harvest season. Harvest times were coordinated with commercial processors (The Morning Star Company, Pacific Coast Producers and Olam Tomato Processors) so that samples could be hand harvested in the same field immediately prior to mechanical harvesting. Table 1 describes the conditions for each of the three harvests of the two cultivars studied in this project.

Harvest method

In each field, roughly 5 kg of red ripe fruits were randomly selected from a row, hand harvested and placed in three-gallon buckets. A mechanical harvester then harvested the remainder of the row using conventional methods, in which fruits are loaded into the gondola of a truck. The truck was followed to the processing plant, where a second 5 kg sample of the mechanically harvested tomatoes was taken randomly from the gondola at the Processing Tomato Advisory Board (PTAB) inspection station. Both hand harvested and mechanically harvested samples were returned to the Department of Food Science and Technology at the University of California Davis, where they were washed and sorted.

Controlled bruising study

Raw materials

Roma tomatoes were purchased from General Produce in Sacramento, CA. Tomatoes were initially sorted based on maturity, particularly color and firmness, and then by size, and those which were 6–9 cm in diameter were used for the study.

Table 1. Conditions during harvests for field study

Harvest	Variety	Time (h)[a]	Air temperature (°C)[b]
1	Sun 6366	2.00	19
2	Sun 6366	3.50	13
3	Sun 6366	4.50	16
4	Heinz 8004	6.25	41
5	Heinz 8004	7.00	39
6	Heinz 8004	2.75	37

[a] Time from harvest in the field to collection at the processing station.
[b] Temperature during harvest reported by the National Weather Service.

Bruise application

Randomly selected 1.5 kg lots of approximately 20 tomatoes each were subjected to a matrix of bruising forces, temperatures and hold times (as outlined in Table 3). Bruising was performed using a universal testing machine (TA-XT2 texture analyzer, Stable Micro Systems, Godalming, UK) with a 7.5 cm compression disk and a test speed of 10 mm s^{-1}. Tomatoes were placed on their sides on the TA-XT2 platform with the stem end on the right and forces of either 0, 75 or 150 N were applied. Preliminary experiments indicated that 150 N was an extreme force that fractured the epidermis of the majority of the tomatoes tested, while 75 N deformed most tomatoes, but not always to the degree where the epidermis fractured. Tomatoes were subjected to these forces at either 21 or 40 °C and analyzed either immediately or after 4 h.

Bruised tomato lots were placed in plastic bags (10″ × 13″, 3 mil STD vacuum pouches, Prime Source, Kansas City, MO, USA) and sealed at 90% vacuum using a Koch UltraVac 250 (UltraSource, Kansas City, MO, USA), then exposed to either 21 or 40 °C in a pre-equilibrated water bath. Samples were held for either 0 h (unheated) or 4 h at one of the two temperatures, then texture and consistency measurements were performed as described in the 'Microwave hot break juice preparation' section.

Temperature dependence study

Raw materials

Roma tomatoes were acquired through General Produce in Sacramento, CA. Tomatoes were initially sorted based on maturity; tomatoes too ripe were defined as soft to the touch and discarded. A size range of 6–9 cm was used to select fruits for the study.

Thermal processing

Tomatoes were randomly divided into lots of 1.5 kg, with approximately 20 tomatoes per lot, and vacuum sealed. Each lot was subjected to a specific temperature (21, 35, 40, 45, 50, 55 or 65 °C) for 1 h in a pre-equilibrated water bath. Five tomatoes from each lot were removed and analyzed for firmness and methanol. The remaining treated tomatoes were then processed into hot break juice and consistency, viscosity and soluble solids content were analyzed.

Microwave hot break juice preparation

Hot break tomato juice was produced using a microwave process that simulates commercial processes, as described by Garcia and Barrett,[16] in order to stop enzymatic activity that would alter

the texture of the juice. Treated tomatoes were cut in half and a random sample of 1.3 kg (±0.005 kg) was placed in a Pyrex 3 qt dish. Dishes were covered with Saran wrap, placed in a commercial 1700 W microwave (RC17S2, ACP Amana, Iron Station, NC, USA) and heated on a high setting for 6 min, then heated for an additional 6 min on a medium setting. The dishes were removed and placed in a 4 °C refrigerator overnight to cool. Cooled, microwaved tomatoes were put through a pulper/finisher (0.033 inch screen, Food Processing Equipment Co., Kalamazoo, MI, USA) and then deaerated under vacuum using a Welch Duo Seal #1374 vacuum pump (Ideal Vacuum Products, Albuquerque, NM, USA). Samples were stored at 4 °C for less than a day until further analysis.

Analytical measurements

Durometer

Firmness was measured using a Rex durometer (type OO model 1600, Rex Gauge Company, Buffalo Grove, IL, USA) mounted on a Rex durometer stand (model OS-2H). Single tomatoes were placed on the base of the stand and the durometer was allowed to sequentially lower onto four equidistant points around the equator of the fruit. Five tomatoes from each treated lot were analyzed prior to microwave hot break processing. This approach was used rather than using a texture analyzer because the durometer is currently being used by some tomato processors as a rapid, non-destructive field instrument.

Methanol

Methanol is the product of the reaction catalyzed by the enzyme PME which results in pectin breakdown. Therefore measuring the methanol content in a whole tomato is used to estimate the activity of PME and de-esterification of pectin. For an accurate determination of the methanol, it is necessary that PME in the tomato be inactivated during and after homogenization to prevent the formation of additional methanol by the action of PME in the homogenate. We have previously shown that homogenizing at low pH in the presence of sodium dodecyl sulfate (SDS) is sufficient for rapid and complete PME inactivation.[17] For this study, individual whole tomatoes were homogenized in a blender with an equal weight of a homogenization buffer containing 0.15 mol L^{-1} HCl and 1 g L^{-1} SDS. Aliquots of the homogenates were centrifuged at 16 100 × *g* for 2 min in an Eppendorf 5415D centrifuge (Hauppauge, NY, USA) and the supernatants were collected and analyzed for methanol.

Methanol analysis was done spectrophotometrically in 96-well plates using alcohol oxidase and the aldehyde-specific reagent Fluoral-P (4-amino-3-penten-2-one) in a modification of methods described previously.[18,19] This method is similar to the commonly used procedure of Klavons and Bennett[20] except that it uses Fluoral-P rather than the Nash reagent to react with formaldehyde. While both procedures produce the same chromophore, the reaction of Fluoral-P with formaldehyde takes place at room temperature and at a pH compatible with alcohol oxidase activity. Thus the Fluoral-P and alcohol oxidase can be added to the reaction at the same time. This not only simplifies the assay but also prevents possible further oxidation of formaldehyde to formic acid by alcohol oxidase, because the formaldehyde reacts with Fluoral-P as it is formed.

A 4 g L^{-1} Fluoral-P solution was prepared by dissolving the reagent in water. Although reported to be unstable in water,[18] we have found that such aqueous solutions are stable for many weeks if stored at 4 °C. This reagent has an absorbance peak at 300 nm with an extinction coefficient of 16 800 L mol^{-1} that can be used to monitor its stability. For the methanol assay a working reagent solution was prepared by mixing equal volumes of the 4 g L^{-1} Fluoral-P solution and a second solution consisting of 0.5 mol L^{-1} phosphate buffer (pH 6.2) and 5 g L^{-1} bovine serum albumin (BSA, fraction V). The inclusion of BSA in this reagent is necessary to prevent inactivation of alcohol oxidase by the SDS present in the tomato samples. Just before use, alcohol oxidase (from *Pichia pastoris*) was added to a final concentration of 0.67 U mL^{-1}.

For the 96-well plate procedure, 50 µL aliquots of the tomato supernatants were pipetted into the plate wells. Assays were started by adding 150 µL of the mixed reagents to each well, then covering and incubating the plates at room temperature. Color formation (peak absorbance at 412 nm) was complete in 45 min and the color was stable for at least 2 h. Absorbances were measured in a Multiskan FC plate reader (Thermo Fisher Scientific, Waltham, MA, USA) equipped with 405 and 550 nm filters and the absorbance difference between these two wavelengths ($A_{405} - A_{550}$) was determined. Absorbance of the colored product at 405 nm was 98% that of the peak at 412 nm; absorbance at 550 nm was zero and thus this wavelength served as a blank. Methanol concentrations (µg g^{-1} fresh weight (FW)) were calculated from the sample absorbance differences and a standard curve of methanol standards.

Bostwick

Microwave hot break juice samples were allowed to equilibrate to 20 °C (±0.5 °C), then a custom-made 50 cm Plexiglas juice Bostwick consistometer was used for measuring consistency. Because juice was being measured, the custom consistometer was made longer than consistometers made for paste in order to account for the lower consistency. The consistometer was leveled on two planes by adjusting screw mechanisms on the bottom of the device. Juice samples were loaded into the holding cell, separated from the trough by a removable door. When the door was opened, the samples flowed down the trough and the distance traveled in 30 s was recorded as the Bostwick value (cm).

Serum viscosity

A 30 g sample of microwave hot break juice was centrifuged at 14 500 × *g* for 10 min at 20 °C in a Dupont Sorvall RC5C centrifuge (Bohemia, NY, USA) and the supernatant was collected. The viscosity of the serum was determined using an Ostwald viscometer calibrated to 30 °C.

Soluble solids

A Bellingham + Stanley RFM 80 refractometer (Basingstoke, UK) was used to determine the soluble solids content (°Brix) of the hot break juice.

Statistical analysis

All statistical analysis was carried out using JMP 9.0 SAS software (SAS Institute, Cary, NC, USA). Durometer and methanol readings were analyzed by type III analysis of variance (ANOVA) and Student's *t*-test or Tukey's honest significant difference (HSD) where applicable. Consistency, serum viscosity and soluble solids were first analyzed by multivariate ANOVA (MANOVA), then type III ANOVA and Student's *t*-test or Tukey's HSD when applicable. All analysis was performed with $\alpha = 0.05$.

Table 2. Average measurements made on hand and mechanically harvested tomatoes and juice

Harvest type	Durometer	Methanol (μg g^{-1} FW)	Bostwick (cm)	Serum viscosity (cSt)	Soluble solids (°Brix)
Hand	79 (2.8)a	43.3 (53.8)a	16.1 (1.8)a	5.68 (2.00)a	5.4 (0.8)a
Mechanical	68 (2.9)b	152.5 (145.6)b	15.2 (1.8)b	5.59 (1.78)a	5.2 (0.4)a

Data in parentheses are standard deviations. Values with different letters in the same column are significantly different (P <0.05).

RESULTS AND DISCUSSION

Field study

Hand harvesting was used in this study as representing the safest and most gentle method the tomato industry could employ while harvesting, in contrast to the more severe commercial process in which the fruit is harvested with a mechanical harvester. Hand harvested tomatoes were significantly firmer (P <0.05) than mechanically harvested tomatoes for all harvests (Table 2). This result may be attributed to the damage sustained during the mechanical harvest as well as to compression and vibration during transportation. Arazuri *et al.*[21] found that tomatoes located in the bottom 30% of transportation trailers were significantly compressed.

Mechanically harvested tomatoes contained significantly more methanol than hand harvested tomatoes (P <0.05) (Table 2). Since methanol is a product of PME activity, the higher methanol content of the mechanically harvested fruit indicates that more pectin de-esterification by PME had occurred in the machine harvested fruit. It is well known that when a tomato is homogenized, PME activity in the homogenate breaks down the pectin, resulting in a rapid accumulation of methanol in the homogenate.[22] The mechanism by which tissue disruption leads to PME activation is not known; however, it has been suggested that PME is physically separated from pectin in the plant cell, perhaps located in a different cellular compartment. The accumulation of methanol in the machine harvested fruit indicates that the level of physical damage and tissue disruption caused by the mechanical harvest and transport is sufficient to cause activation of PME.

Methanol accumulation was significantly higher (P <0.05) in tomatoes harvested on warmer days and/or when there was a longer period of time between harvesting and processing (data not shown). Higher temperatures have been shown to increase PME activity in tomatoes, with activities nearly 100 times greater at 65 °C than at 25 °C.[17] A longer time from harvest to processing would increase the time for the PME in the damaged portions of the tomato to act on the pectin.

Hot break juice made from mechanically harvested tomatoes had a higher consistency (lower average Bostwick) than juice made from hand harvested tomatoes (P <0.05) (Table 2). It is well known that after demethylation by PME, pectin is more susceptible to depolymerization by PG. Hydrolysis of pectin by PG causes a loss of juice consistency. Thermal inactivation of PG is a key reason for the initial hot break step in the manufacture of high-consistency tomato products.[6,17,23] It was initially postulated that because mechanically harvested fruits were less firm and contained more methanol (an indicator of greater de-esterification of pectin by PME), the resulting juice would be more susceptible to pectin depolymerization by PG and thus have a lower consistency. However, quite the opposite was observed. In five out of the six harvests the mechanically harvested fruit had a lower Bostwick value than the hand harvested fruit.

One possible explanation for this is that the higher PME activity in the mechanically harvested fruit resulted in an increased number of free carboxyl groups on demethylated pectin that could then be bound by calcium, creating a stronger pectin network and a juice with a higher consistency. Another hypothesis for the greater consistency in juice made from mechanically harvested fruits is the potential loss of tomato fluid during harvest and transportation. As tomatoes are harvested and transported, cracks in the epidermis are sometimes formed which allow for expulsion of liquid from the locules. In a previous study, tomato hoppers lined with plastic and juice wells (12 inch × 18 inch × 36 inch) were installed in the bottom of the hoppers.[24] Liquid of up to 4 inch depth was measured at the bottom of tomato transportation hoppers after a 100 mile haul from field to cannery. This resulted in an average of 3000 lb of juice loss per truck, or 6% of the total load. If this liquid is not recovered or washed away in the flume, the resulting paste may have a higher consistency due to the loss of liquid, essentially concentrating the juice.

A final reason for the improved consistency effect may be that softening of bruised tissues facilitated juice extraction. York *et al.*[10] found that sometimes damaged ripe fruits resulted in paste with a higher consistency than that from undamaged tomatoes. These authors speculated that when damaged tissue was sufficiently softened, more of the tomato solids could be forced through the pulper/finisher screen during processing, resulting in a juice with higher consistency.

Mean serum viscosity was not significantly affected by harvest method (P >0.05) (Table 2). Serum viscosity is determined primarily by the amount and degree of polymerization of pectins in the juice serum and is greatly affected by PG activity. Because serum viscosity was not affected by the harvest method, it may be assumed that PG activity was similar for both harvest methods. This supports the first hypothesis discussed above, that Bostwick consistency was greater in mechanically harvested tomatoes, and the theory that PME-catalyzed demethylation allows for calcium binding of pectin networks to increase strength and produce a juice with greater consistency.

Soluble solids content was not significantly affected by harvest method (P >0.05) (Table 2).

Controlled bruising study

Applying a force of 75 or 150 N to the surface of a tomato significantly decreased (P <0.05) its firmness (Table 3). This loss of firmness was unchanged by holding the tomato at 21 °C for 4 h following the bruising. Increasing the holding temperature to 40 °C resulted in a significant decrease in firmness compared with fruit held at 21 °C for the same time (P <0.05); however, this loss of firmness was independent of whether or not force was applied. Tomatoes bruised at 150 N and held for 4 h at 40 °C had structurally degraded to a point where the durometer could not register a force reading.

Bruising by itself did not lead to any significant accumulation of methanol either with or without an additional 4 h holding time at 21 °C (P >0.05). This result is consistent with Van linden

Table 3. Texture and methanol accumulation data of whole fruit and hot break processed juice subjected to various forces, times and holding temperatures from controlled bruising study

Force (N)	Temperature (°C)	Time (h)	Durometer	Methanol (μg g^{-1} FW)	Bostwick (cm)	Serum viscosity (cSt)	Soluble solids (°Brix)
0	21	0	77 (4.4)a	21.8 (5.8)a	15.1 (0.5)a	5.36 (0.13)a	3.7 (0.1)a
	21	4	76 (5.0)a	24.5 (1.3)a	15.4 (0.6)a	5.43 (0.22)a	3.8 (0.1)a
	40	4	64 (9.8)c	89.4 (3.7)a	14.7 (0.4)b	4.66 (0.25)b	3.7 (0.1)a
75	21	0	66 (9.8)b	25.1 (2.7)a	14.8 (0.4)a	4.90 (0.74)a	3.8 (0.3)a
	21	4	69 (6.2)b	16.2 (1.3)a	15.7 (0.7)a	5.16 (0.27)a	3.7 (0.0)a
	40	4	60 (11.0)c	60.8 (8.5)b	14.5 (0.7)b	4.82 (0.25)b	3.8 (0.1)a
150	21	0	57 (13)b	28.6 (4.4)a	14.5 (0.1)a	4.91 (0.04)a	3.7 (0.0)a
	21	4	55 (8.3)b	37.2 (11.6)a	16.2 (1.6)a	5.21 (0.47)a	3.8 (0.1)a
	40	4	ND	140.0 (24.1)b	14.4 (0.7)b	4.05 (0.18)b	3.8 (0.0)a

Data in parentheses are standard deviations.

et al.,[5] who found that bruising a tomato did not activate PME within 3 h. Holding the fruit for 4 h at 40 °C caused significant methanol accumulation (P <0.05) even in the absence of any bruising (Table 3).This effect is likely due to temperature activation of PME, as has been observed previously with green beans and diced tomatoes.[17]

The force applied to whole fruit had no significant effect on the Bostwick consistency of hot break juice made from that fruit (P <0.05) (Table 3). Holding tomatoes for 4 h at 40 °C resulted in a higher consistency (lower Bostwick) than holding for 4 h at 21 °C. This was true whether or not the fruit was subjected to any applied force. This increase in consistency is possibly due to the firming effect of PME. As the methanol data show, when tomatoes are heated to 40 °C, substantial PME activity occurs during the 4 h hold, which may lead to an increase in consistency. It is also possible that treating tomatoes at higher temperatures caused a softening of cell wall material, allowing for more cell wall polymers to move into the liquid phase, resulting in an increase in consistency.[25]

Increasing the temperature to 40 °C significantly decreased serum viscosity (P <0.05) compared with fruit held at 21 °C for the same amount of time (Table 3). This result indicates that PG was actively degrading pectin in the 40 °C samples; however, the consistency was higher for the same samples. This result may be explained by the hypothesis of York *et al.*[10] that the softened bruised tissue may have been extracted more readily through the pulper/finisher screen, leading to an apparent increase in consistency.

Soluble solids content was not significantly affected by any parameter of this study (P >0.05) (Table 3). York *et al.*[10] found that fruit that had an increased consistency due to damage also showed an increase in insoluble solids or a decrease in soluble solids. Our study found that bruising did not cause a change in consistency, nor was a change in soluble solids observed.

Temperature dependence study

Exposure of whole tomatoes for 1 h to temperatures between 21 and 45 °C did not result in a significant change in methanol content (P >0.05). As temperature increased to 50, 55 and 65 °C, methanol content increased significantly between each temperature interval (P <0.05) (Fig. 1). Methanol contents in whole tomatoes that were held at the same temperatures for 1 h, cooled and held at 21 °C for a further 23 h are displayed in the same figure. While the 20 and 35 °C treatments showed no significant

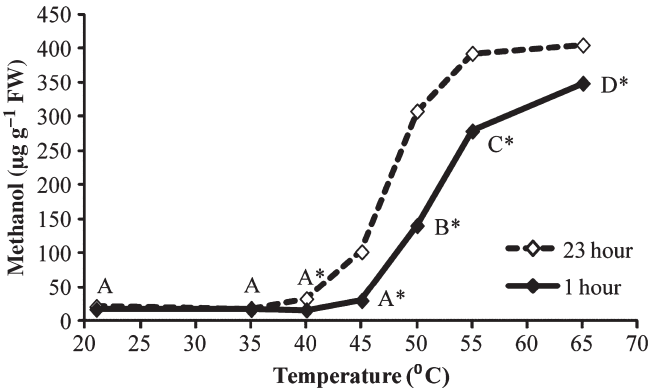

Figure 1. Methanol accumulation in whole tomatoes held for 1 h and processed or held for 1 h, cooled, held for an extra 23 h at 21 °C and processed. Data points with different letters are significantly different (P <0.05) within the 1 h group. Data points with an asterisk (*) represent a significant difference between the 1 and 23 h data points at the same temperature (P <0.05).

increase during the extended hold time (P >0.05), 40–65 °C treatments led to a significant increase in methanol content between tomatoes held for 1 h and those exposed to the same temperature but held for an additional 23 h at 21 °C (P <0.05). This indicates that PME was irreversibly activated even after the fruit was cooled to a temperature which was shown not to induce methanol accumulation.

Firmness of whole tomatoes was significantly reduced (P <0.05) by exposure to temperatures of 40 °C or higher for 1 h. This loss of firmness was small at 40 and 45 °C but substantial as the temperature was increased to 55 °C (Fig. 2). These results coincide with those for other commodities exposed to temperatures between 0 and 45 °C, such as peas, apples and apricots.[26]

When whole tomatoes were held at 35 °C, the Bostwick value of the resultant juice was significantly lower (P <0.05) (indicating increased consistency) than that of juice from fruits held at 21 °C (Fig. 3). As shown by the methanol content (Fig. 1), PME is not active at this temperature, so the increased consistency is not due to polyvalent cations binding demethylated pectin polymers. The increase in consistency may be due to an increased hydrophobic effect that occurs between pectin chains when the temperature is elevated. It may also be due to a softening of cell wall material, increasing the amount of polymers migrating into the liquid phase, resulting in an increase in viscosity.[27]

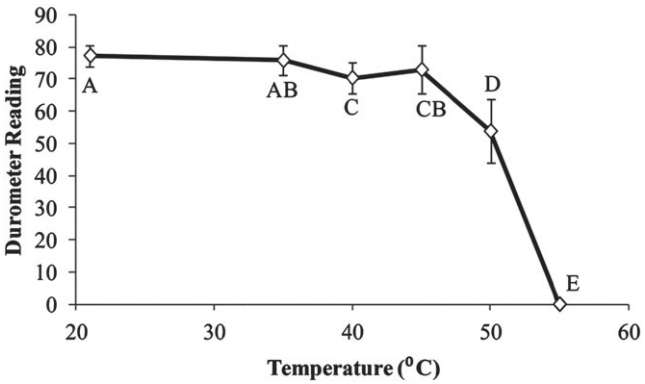

Figure 2. Durometer readings of whole fruits exposed to a range of temperatures for 1 h. Data points with the same letter are not significantly different ($P > 0.05$). Standard error bars are shown.

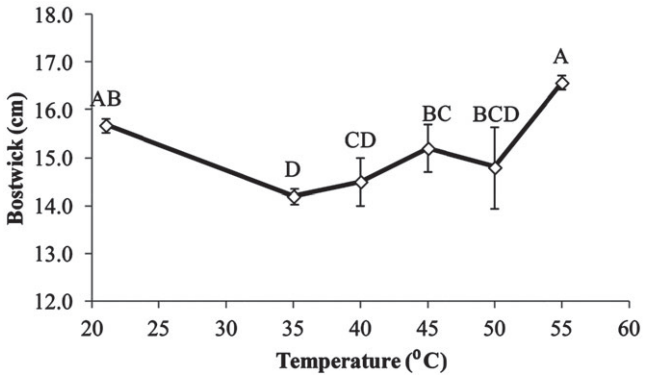

Figure 3. Bostwick consistency measurements of juice made from tomatoes exposed to a range of temperatures for 1 h prior to hot break processing. Data points with the same letter are not significantly different ($P > 0.05$). Standard error bars are shown.

Exposure of whole fruits to temperatures from 40 to 50 °C produced juice consistencies that on average decreased (indicated by higher Bostwick values) with increasing temperature; however, considerable variability between replicate trials conducted at the same temperature was observed. Methanol data (Fig. 1) showed that PME activity was just starting to increase at these temperatures.

Juices made from tomatoes pre-treated at 55 °C were significantly less consistent ($P < 0.05$) than the juices from all other temperature treatments except 21 °C. At 55 °C, both PME and PG[27] are active, thus PG-catalyzed depolymerization of pectin polymers likely occurred, leading to the observed loss of consistency. It would be beneficial in future studies to determine the degree of methylesterification of pectin in the 21–55 °C treatments.

Serum viscosity decreased significantly at 50 and 55 °C ($P < 0.05$) (Fig. 4). The trend in serum viscosity correlates well with the production of methanol ($R^2 = 0.98$; data not shown), which reinforces the hypothesis that enzymatic depolymerization and solubilization of pectin molecules is causing a decrease in the consistency at the higher temperatures used in this study. However, loss of serum viscosity at the higher temperatures may also be due in part to conformational changes in the pectin molecules caused by thermal treatments rather than enzymatic depolymerization.[28]

Per cent total solids, soluble solids and insoluble solids were not significantly affected by pre-treatment temperature ($P > 0.05$) (data not shown). Other studies have shown that Bostwick value

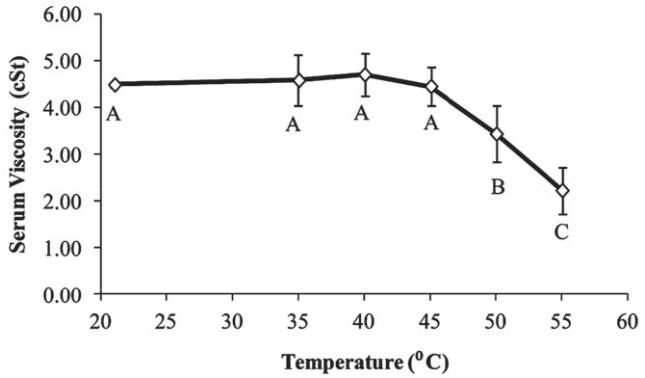

Figure 4. Serum viscosity of juice made from tomatoes exposed to a range of temperatures for 1 h prior to hot break processing. Data points with the same letter are not significantly different ($P > 0.05$). Standard error bars are shown.

is directly correlated with solids content.[10,29] York *et al.*[10] found a high inverse correlation ($R^2 = -0.89$) between insoluble solids and Bostwick measurements; however, their study focused mainly on bruising and not on temperature dependence.

CONCLUSIONS

Current tomato harvest practices have a detrimental impact on the firmness of tomato fruits; however, this loss of firmness improves the consistency of the processed juice and has no significant impact on serum viscosity. Temperature at harvest was found to significantly affect the consistency of processed juice, while the degree of bruising did not. At temperatures common in California during the tomato season, e.g. 35–40 °C, PME was found to be irreversibly activated. Tomatoes harvested and processed at these temperatures are likely to have a better juice consistency than tomatoes harvested at a lower temperature. Further sensory studies should be performed to determine if this consistency change is noticeable to consumers to warrant action by tomato processors.

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