QUALITY ATTRIBUTES OF PROCESSED TOMATO PRODUCTS: A REVIEW

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ABSTRACT
Tomato is the second largest vegetable crop in dollar value in the United States and other parts of the world. World production of tomatoes for processing stands over 20 million tons per annum, with more than 50% in the United States. Processed tomato products are an important source of minerals and vitamins in the diet of U.S. consumers. An American consumes over 12 kg of processed tomatoes per year excluding tomato ketchup and sauce. In addition to nutritive value, the color, consistency, and flavor are the major quality attributes of processed tomato products which influence the buying behavior of the consumer. These attributes are highly variable and change with changes in fruit cultivar, growing conditions, and/or processing parameters. This paper reviews the quality factors of processed tomato products along with the factors that affect them.

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INTRODUCTION

Tomato (*Lycopersicon esculentum*) is one of the most important vegetable crops of the family Solanaceae. The family Solanaceae includes about 1500 tropical and subtropical species; the genus *Lycopersicon* consists of only eight species and is subdivided into two subgenera: *Eulycopersicon* and *Eriopersicon*. Fruits of the *Eulycopersicon* are usually red or yellow in color when ripe, and include the cultivated tomato. Fruits of the *Eriopersicon* remain green or purple green throughout development (1,2). The first description of several tomato varieties was made by Miller in 1768; hence many texts refer to *L. esculentum* Mill. (3) The tomato is native to South America and Mexico, and was first eaten by native Mexicans, who called it "tomati." It was domesticated in Mexico, where it was planted along with the maize. The tomato was little known as an edible vegetable in the United States until 1830–1840 (3). It was during this period that tomatoes gained popularity and were sold in the market. Large-scale cultivation of the tomato did not begin until about a century ago and it became generally cultivated only after the First World War. Its increasing popularity led to the introduction of hundreds of varieties and a huge increase in tomato production. Now it is consumed all over the world and is the second largest vegetable crop in terms of dollar value (1,3). Table 1 gives country-by-country production of tomato fruit worldwide. World production of tomatoes for processing exceeds 20 million metric tons, with more than 50% produced in the United States (Table 2).

Tomato fruit normally contains 5–10% dry matter, of which 1% is skin and seeds (1). Reducing sugars constitute nearly 50% of the dry matter. Glucose and fructose are the main sugars present, though minute quantities of other sugars have been reported, such as raffinose, arabinose, xylose, galactose; and sugar alcohol, myo-inositol (1,4–9). Sucrose is also found but its concentration rarely exceeds 0.1% of fresh fruit mass (5). In the initial stages of development, glucose is present in higher concentrations than fructose (glucose:fructose ratio = 1.8). During growth and ripening, the sugar content increases significantly and the glucose:fructose ratio gradually decreases, depending upon variety, to around 1 (5, 10). Singh and Saini (11) reported an increase in reducing sugars during the concentration of tomato juice into paste. Alcohol-insoluble solids (proteins, pectins, cellulose, and hemicelluloses), organic acids, minerals, pigments, vitamins, and lipids make up the other 50% of total dry matter (1). Organic acids, primarily citric and malic acids, constitute more than 10% of the dry content of tomato (1,11–13). Minute quantities of many other acids have also been reported (1,2). Loiudice et al. (14) measured the compositional characteristics of 11 lines of hybrid and wild-type cultivars of San Marzano tomatoes and reported that three amino acids—glutamic acid, γ-aminobutyric acid, and glutamine—comprise as much as 65% of the total amino acids present in fruits. They concluded that, from a compositional viewpoint, it is difficult to differentiate between pure San Marzano lines and
<table>
<thead>
<tr>
<th>Country</th>
<th>Production (1000 MT)</th>
<th>% World</th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>70,623</td>
<td></td>
</tr>
<tr>
<td>United States</td>
<td>10,665</td>
<td>15.10</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>8,665</td>
<td>12.26</td>
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<tr>
<td>Turkey</td>
<td>6,150</td>
<td>8.71</td>
</tr>
<tr>
<td>Italy</td>
<td>4,639</td>
<td>6.56</td>
</tr>
<tr>
<td>India</td>
<td>4,600</td>
<td>6.51</td>
</tr>
<tr>
<td>Spain</td>
<td>2,694</td>
<td>3.75</td>
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<td>Brazil</td>
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<td>1,780</td>
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<tr>
<td>Iran</td>
<td>1,600</td>
<td>2.26</td>
</tr>
<tr>
<td>Russian Federation</td>
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<tr>
<td>Uzbekistan</td>
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<td>1.63</td>
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<td>Ukraine</td>
<td>1,148</td>
<td>1.63</td>
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<td>Chile</td>
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<td>Romania</td>
<td>799</td>
<td>1.13</td>
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<td>France</td>
<td>798</td>
<td>1.13</td>
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<tr>
<td>Japan</td>
<td>750</td>
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<td>Argentina</td>
<td>730</td>
<td>1.03</td>
</tr>
<tr>
<td>Portugal</td>
<td>718</td>
<td>1.02</td>
</tr>
<tr>
<td>Netherlands</td>
<td>640</td>
<td>0.91</td>
</tr>
<tr>
<td>Algeria</td>
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<td>Jordan</td>
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<td>0.69</td>
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<td>Saudi Arabia</td>
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<tr>
<td>Canada</td>
<td>475</td>
<td>0.67</td>
</tr>
<tr>
<td>Iraq</td>
<td>460</td>
<td>0.65</td>
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<td>Oceania</td>
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<td>0.65</td>
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<tr>
<td>Hungary</td>
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<td>Niger</td>
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<td>0.56</td>
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<tr>
<td>Syria</td>
<td>395</td>
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<tr>
<td>Australia</td>
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<td>Israel</td>
<td>364</td>
<td>0.52</td>
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<td>Poland</td>
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<td>Colombia</td>
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<td>Azerbaijan</td>
<td>337</td>
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<tr>
<td>Kazakhstan</td>
<td>320</td>
<td>0.45</td>
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<tr>
<td>Indonesia</td>
<td>245</td>
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<tr>
<td>Lebanon</td>
<td>235</td>
<td>0.33</td>
</tr>
<tr>
<td>Armenia</td>
<td>230</td>
<td>0.33</td>
</tr>
<tr>
<td>Venezuela</td>
<td>200</td>
<td>0.28</td>
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Source: Data from FAO, "Food and Agriculture Organization, Year Book," 1993, Vol. 47, pp. 129-130.
Table 2. World Production of Processing Tomatoes (1990, Descending Rank)

<table>
<thead>
<tr>
<th>Country</th>
<th>Production (1000 MT)</th>
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<tbody>
<tr>
<td>United States</td>
<td>9,307</td>
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<tr>
<td>Italy</td>
<td>3,850</td>
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<tr>
<td>Turkey</td>
<td>1,500</td>
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<td>Greece</td>
<td>1,150</td>
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<td>Spain</td>
<td>1,134</td>
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<tr>
<td>Portugal</td>
<td>760</td>
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<tr>
<td>Canada</td>
<td>580</td>
</tr>
<tr>
<td>France</td>
<td>540</td>
</tr>
<tr>
<td>Mexico</td>
<td>365</td>
</tr>
<tr>
<td>Israel</td>
<td>300</td>
</tr>
<tr>
<td>Taiwan</td>
<td>182</td>
</tr>
</tbody>
</table>

Source. Data from Ref. 3.

hybrids without a careful morphological examination of the product. Table 3 gives the average composition of fresh tomato fruit and processed products.

In addition to these nutrients, tomato also contains some potentially toxic glycoalkaloids: tomatine and solanine. These alkaloids protect the tomato plant against microorganisms and pests (15). Tomatine is the most common alkaloid present in tomatoes. Young green tomato fruits are high in tomatine (16), which is a cause for concern if many are consumed. However, as the fruit ripens, tomatidine (a precursor of tomatine) is depleted and little if any can be found in fully ripe tomatoes (17–20). Interestingly, lower levels of tomatine were found in tomatoes that were permitted to ripen on the plant versus tomatoes that were artificially ripened (21). Fully ripened tomatoes have tomatine levels of less than 5 mg/kg while green fruits of wild species have levels as high as 3390 mg/kg (22). Tomatine, however, is hydrolyzed during storage of processed products made from immature tomatoes due to the acidic nature of the product (23). Solanine is present in a small amount but is not considered a health hazard. Davies and Hobson (2) described in detail the different constituents of fresh tomato fruit, along with the factors influencing their concentration.

More than 80% of processing tomatoes produced are consumed in the form of processed products such as tomato juice, paste, puree, catsup, sauce, and salsa. The average American consumes over 12 kg of processed tomatoes per year, compared to 27 kg for all commercially processed vegetables (3). In the manufacturing process, tomatoes are washed, sorted, and then processed into juice. Tomatoes can be processed by either a hot- or cold-break method to extract the juice. In the hot-break method, chopped tomatoes are heated rapidly to at least 82°C to
Table 3. Composition of Fresh Tomato and Tomato Products (100 g)

<table>
<thead>
<tr>
<th>Product</th>
<th>Tomato</th>
<th>Juice</th>
<th>Paste</th>
<th>Ketchup</th>
<th>Chili sauce</th>
<th>Puree</th>
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<tr>
<td>Water (%)</td>
<td>93.5</td>
<td>93.6</td>
<td>75</td>
<td>68.6</td>
<td>68</td>
<td>87</td>
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<tr>
<td>Carbohydrate (g)</td>
<td>4.7</td>
<td>4.3</td>
<td>18.6</td>
<td>25.4</td>
<td>24.8</td>
<td>39</td>
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<tr>
<td>Protein (g)</td>
<td>1.1</td>
<td>0.9</td>
<td>3.4</td>
<td>2.0</td>
<td>2.5</td>
<td>1.7</td>
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<tr>
<td>Fat (g)</td>
<td>0.2</td>
<td>0.1</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Ash (g)</td>
<td>0.5</td>
<td>1.1</td>
<td>2.6</td>
<td>3.6</td>
<td>4.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Ascorbic acid (mg)</td>
<td>23</td>
<td>16</td>
<td>49</td>
<td>15</td>
<td>16</td>
<td>33</td>
</tr>
<tr>
<td>Vitamin A (IU)</td>
<td>900</td>
<td>800</td>
<td>3300</td>
<td>1900</td>
<td>1400</td>
<td>1600</td>
</tr>
<tr>
<td>Food energy (calories)</td>
<td>22</td>
<td>19</td>
<td>82</td>
<td>106</td>
<td>104</td>
<td>39</td>
</tr>
</tbody>
</table>

Source: Data from Ref. 3.

Inactivate pectolytic enzymes. The activity of pectic enzymes is greatly enhanced as the temperature is increased to about 60°-66°C. Beyond this temperature, the activity is reduced until it is inactivated at about 82°C (24). In the cold-break process, the tomatoes are chopped and then the juice is extracted following mild heating. The cold-processed product has a more natural color and a fresher tomato flavor (3). However, the product has low consistency and may separate during storage. The hot-break process, due to inactivation of the pectic enzymes and more efficient extraction of pectic substances, gives a more viscous and homogeneous product which does not separate upon storage.

Juice from tomato fruits may be extracted by two main types of extractors, screw or paddle. At any given speed of finisher blades, larger screen size allows not only more pulp but also more serum to flow through the sieve, which results in higher yield of juice. Furthermore, the high rotating speed results in greater centrifugal force, which allows more tomato juice and serum to pass through (25). Depending upon the type of equipment used, yield of juice can vary from 29.4% to 91.5% (26). It is, however, advisable to extract only about 70% of possible juice yield because this will have relatively more soluble solids, which will improve flavor, and a lower percentage of the insoluble solids which would reduce the quality of the finished products (27).

In manufacturing other tomato products (pulp or puree soluble solid [SS] = 8.0–24.0%; tomato paste SS = 24.0% or more; concentrated tomato juice SS = 20.0–24.0%), juice is concentrated in tanks with steam coils or vacuum evaporators. For concentration, vacuum evaporators are preferred because concentration is done at lower temperatures, thus preserving color and flavor (24). Depending upon the amount of water removed from juice, either puree or paste is formed. The processing protocol for ketchup is the same as that for paste or puree, with additional cooking to assimilate the flavoring ingredients.
Over $9 \times 10^4$ tons of tomatoes are processed annually in the United States, with California producing 85% of the total. Pack distribution of processed tomato products for the U.S. market is estimated as follows: 35% sauces, 18% paste, 17% canned tomatoes, 15% ketchup, and 15% juice. Since 1991 salsa has replaced ketchup as the number 1 selling condiment in dollar sales and its sales increased by 9.8% in 1993 from the same period in 1992. The market for processed tomato products is expected to grow in the future (3).

As for all products, marketing of tomato products is influenced by their quality. In addition to nutritional value, the sensory characteristics are the major attributes influencing the buying behavior of the consumers. Attractive bright red color, good aroma, high consistency, low pH and high acidity, and low serum separation are some of the factors that favorably influence quality of the product and the consumer’s choice. The present review discusses the quality parameters of tomato products and the factors influencing them.

QUALITY ATTRIBUTES

Color

Color has a strong influence on the buying behavior of the consumer (28). Consumers notice color first, and their observation often provides preconceived ideas about other quality factors such as flavor or aroma. In the case of tomatoes and tomato products, color serves as a measure of total quality. It is important, therefore, to make a favorable initial impression with standard and familiar colors that consumers both want and expect to see (3). Color in the tomato is due to carotenoids. Carotenoids are a class of polyene compounds with yellow to red color. Almost all carotenoids either are or are derived from tetraterpenes, C-40 compounds with a carbon skeleton built up from eight C-5 isoprene units. Many types of carotenoids have been isolated and quantified in the tomato fruit and in processed tomato products: lycopene, lycopene-5,6-diol, α-carotene, β-carotene, γ-carotene, δ-carotene, lutein, xanthophylls (carotenol), neurosporene, phytoene, and phytofluene. The cis-isomer of β-carotene was detected only in processed product and was absent in raw tomato fruits (29,30). The chemical formula of carotenoids is C_{n}H_{m} while that of xanthophyll, a carotene alcohol is C_{n}H_{m}(OH)_{2}. Lycopene is the major carotenoid of tomato and comprises about 83% of the total pigment present. Beta-carotene is about 3–7% of the total carotenoids in tomato fruit (3). The chemical structures of lycopene and β-carotene are shown.

Carotenoids are more soluble in organic solvents than in water. In nature they occur in small globules suspended in the tomato pulp. The outer pericarp in tomato fruit is highest in total carotenoids and the locular contents are highest in carotene. Carotenoids are chemically more stable than other pigments of plant or animal origin such as chlorophyll, anthocyanin, hemoglobin, and myoglobin (3). They undergo degradation, however, during processing and preservation of foods.
Degradation of carotenoids and the color of processed tomato products is affected by a number of factors as described below.

Color loss of tomato juice is accelerated by high temperature and longer storage due to degradation of color pigments (Fig. 1) (31). Wiese and Dalmasso (32) reported significant increase in the hue angle of tomato juice after processing and storage, indicating loss of red color. Color retention in tomato products is better at lower temperature (33,34). The main cause of carotenoid degradation in foods is oxidation. In processed foods, oxidation is complex and depends upon many factors, such as processing conditions, moisture, temperature, and the presence of pro- or antioxidants and lipids. Use of fine screens in juice extraction enhances

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**Figure 1.** Effect of time and temperature on color ($a_L/b_L$ ratio) of tomato juice. $a_L/b_L$ gives the chroma or hue values for any given $L$ value. (Modified from Ref. 31.)
oxidation of pigments due to the large surface exposed to air and metal. Therefore, use of coarser screens increases the retention of color of tomato products (35). This, however, may have implications for other quality parameters of tomato products as discussed later. Beta-carotene is more susceptible to degradation at lower water activity ($a_w$). As water activity increases, stability increases (36–40). Therefore the carotenoids may be partially destroyed in tomato products of low water content (3). The presence of metal ions has been reported to decrease stability while antioxidants and lipids enhance the stability of β-carotene (36).

The amount of carotenoids in tomato products is dependent on the variety and on growing conditions. Fruits grown in the greenhouse either in summer or winter are lower in carotene content than fruits produced outdoors during summer, and fruits picked green and ripened in storage are very much lower in carotene than vine-ripened fruits (3). The amount of sugar, acids (pH), and amino acids, as well as time and temperature of processing also affect the color of processed tomato products by causing the formation of brown pigments.

There are different systems to grade the color of tomato and tomato products. The major systems available for color matching and comparison are: Ridgway Chirb, the Maerz and Paul color dictionary, Munsell color system and charts, the CIE or ICI system, the Macbeth–Munsell disk colorimeter, the Hunter color and color difference meter, and Agtron instruments. These measurements can be translated into a standard developed by the International Commission on Illumination in 1931 (3).

**Flavor**

Flavor is an important quality attribute of processed tomato products. Like other quality parameters, it is also affected by agricultural practices, time of harvest, postharvest treatment, and genetic control (cultivar) (41). The characteristic sweet–sour taste and the flavor intensity of tomato and tomato products are affected by almost all of the tomato constituents. They may influence the flavor directly as a flavor substance or indirectly by providing either an appropriate medium for chemical or biochemical reactions leading to the formation of the flavor; or by catalyzing the above reactions; or by acting as a precursor of the flavor substances; or by absorbing some volatile substances that contribute to flavor; or by affecting the tension of the aroma components in the head space (1).

Stevens et al. (42) reported a significant correlation between overall flavor intensity and citric acid and fructose content, as well as the glucose–citric acid interplay. The highest overall flavor intensity was found in samples where both sugar and titratable acid contents were high. Addition of reducing sugars (fructose/glucose) and citric acid to fresh diced tomatoes improves the flavor acceptability of the products significantly (43).
Of the 400 volatiles identified in tomato fruits, only the following have been reported to play important roles in fresh tomato flavor: hexanal, trans-2-hexanal, cis-3-hexanal, cis-3-hexenol, trans-2-trans-4-decadienal, 2-isobutythiazole, 6-methyl-5-hepten-2-one, 1-penten-3-one, and b-ionone (1,44–47). Dalal et al. (48) reported differences in the concentrations of volatile compounds among field-grown, greenhouse-grown, and artificially ripened tomatoes. High concentrations were found in field-grown tomatoes while artificially grown tomatoes contained the lowest concentration of volatiles. Differences between the flavors of different varieties are due to differences in quantitative proportions of the volatile substances. Volatile substances develop partly during ripening, partly during the comminution of the ripe fruit, as an effect of the activated enzymes (1). Kazemi and Hall (49) showed that certain tomato volatiles are produced enzymatically after tissue damage.

Some workers reported that processed product flavor comes from hydrolysis of glycosides present in tomato fruits (50,51). Buttery et al. (52) isolated a glycoside fraction from fresh tomatoes and hydrolyzed it at various pH levels to give the volatile aglycon. Major volatiles identified at all pH levels included 3-methylbutyric acid, 3-butyl-2-methylpropionic acid, 2-methylbutyric acid, 2-phenylethanol, p-anisaldehyde, 2-methylbutanol, linalool, limonene, ß-pinene, linalool oxides, a-terpineol, 2-vinylguaiacol, and 4-vinylphenol. They also identified other compounds present in small proportions.

The effect of processing on the volatile constituents of tomato products was reported by many workers (51,53–55). Using the "aromagram," Ginnette et al. (53) showed that many tomato volatiles were lost in the process of producing tomato paste. Buttery et al. (51) identified 21 additional volatile compounds in tomato paste which were not reported earlier. Dimethyl trisulfide and 1-octen-3-one were reported to be the most potent odorants. They attributed the origin of these compounds to the hydrolysis of glycosides.

Miers (56) reported that hydrogen sulfide and methyl sulfide modify the overall aroma of processed tomato products. Buttery et al. (44) reported that methyl sulfide with a threshold value of 0.3 ppb is a sure contributor to the aroma of heated tomato products. Of the other compounds, linalool, with a threshold value of 6 ppb, is considered to contribute to the cooked aroma of processed tomato products. The precursor for methyl sulfide was determined to be an S-methyl methionine sulfonium salt (57). Heating the sulfonium salt yields homoserine and methyl sulfide. Processed tomato products contain several sulfur amino acids which may react during processing to give rise to these sulfides (56). During tomato processing, the compounds responsible for flavor development undergo changes that may or may not be desirable. During processing, some of the volatile compounds evaporate while others may be formed due to breakdown of sugars and carotenoids. Depending upon the time and temperature of processing, reducing sugars and amino acids decrease while acid content increases due to the formation of pyrroloidine carboxylic acid (1).
The off-flavor occasionally appearing in heat-treated vegetable products has been ascribed to the formation of pyrrolidone carboxylic acid (58–64). Shallenberger et al. (59) and Moyer et al. (26) reported pyrrolidone carboxylic acid to have, particularly in the pH range 5–6, an unpleasant phenolic or bitter flavor. Nelson and Hoff (54) reported a big difference in the volatile components of raw and heat-processed tomato samples. Methyl sulfide, which was absent in fresh fruit, was formed during heat processing. They also reported significant changes in the concentration of acetaldehyde, acetone, methanol, and hexanal as a result of processing. Sieso and Crouzet (65) also reported the effect of processing on volatiles present in tomato products, mainly in canned tomato juice and paste. They identified 16 components and reported that important heat-induced volatiles produced included furfural, linalyl acetate, and 2-methyl-2-hepten-6-one. Chung et al. (55) reported a decrease in the low-boiling volatiles and an increase in middle- and high-boiling components during the processing of juice to paste.

In addition to the amino acids and fatty acids, the pigments and sugar components of tomato play an important role in determining the flavor of processed products. The carotenoids in tomato products undergo oxidative degradation leading to the formation of terpenes and terpene-like compounds. Cole and Kapur (66) reported the formation of 6-methylhept-5-en-2-one and acetone when lycopene is oxidized. Buttery et al. (67) showed that farenysyl acetone and generyl lactone are derived from lycopene. Formation of α- and β-ionones, toluene, and para-xylene has also been reported in heat-processed tomato products (49,66). Beta-carotene is destroyed in a coupled oxidation reaction with linoleate which is catalyzed by lipoxidase (68,69). Blain et al. (70) found a water-soluble fraction in tomato which bleached carotenones in the presence of linoleate. It was not a lipoxide but acted like hematin. Stevens (71) found a relationship between polyene–carotene content and volatile composition of tomatoes. Many Maillard reaction products, volatile carbonyls and sulfur compounds, are formed and may affect the aroma of the processed tomato products (72–76). Other decomposition products reported in tomato products are furan, pyrrole, and pyrazine, which also affect the aroma of processed tomato products (77).

**Consistency (Viscosity)**

Viscosity is a measure of the resistance offered by a fluid to the relative motion of its parts. Mathematically, it is the ratio of resistance to shear to rate of shear. In a liquid, if resistance to shear is directly proportional to rate of shear, the liquid is called a Newtonian liquid (e.g., water). A non-Newtonian liquid is one in which resistance to shear is not linearly related to the rate of shear. Most food products, including tomato products, exhibit non-Newtonian characteristics.

Consistency, or gross viscosity, is paramount as a quality attribute in determining the acceptability of tomato products to the consumer and is an integral part
of the quality grade standard. The consumer probably evaluates consistency second only to color as a measure of quality. Therefore, the measurement, control, and maintenance of viscosity is mandatory for high-quality products. In addition to its role in product quality, consistency also has economic implications for tomato processors. Higher consistency lowers the amount of tomato needed in a product to obtain a certain level of quality, thus reducing the cost of the product. Presently, gross viscosity of puree and paste is generally determined by the Bostwick consistometer (developed by E. P. Bostwick) and is referred to as “Bostwick consistency,” although other instruments (e.g., the Brookfield viscometer) are also available. The Bostwick consistometer measures the consistency of a viscous material by determining how far the material flows under its own weight along a sloped surface in a given period of time. It measures the shear stress under the fixed condition of shear rate whereas efflux viscometers (e.g., the Libby tube used to determine the viscosity of the juice, and the Cannon-Fenske viscometer used to determine serum viscosity) measure shear rates under fixed conditions of shear stress.

Processed tomato products consist of disintegrated cells of the pericarp mixed in a clear serum. Their consistency is dependent upon a number of factors including cultivar, geographical location, fruit maturity, processing conditions, solid level, viscosity of the serum, and amount and physical characteristics of the cell walls. The change in Bostwick consistency of tomato juice with change in solid concentration is related to the water-insoluble solids (WIS); total solids (TS) ratio and the serum viscosity of the clarified serum. The WIS:TS ratio is a function of heat treatment and screen size, while the serum viscosity is dependent upon the effectiveness of the heat treatment in destroying the enzyme systems acting on the high molecular weight polymeric substances that are responsible for this attribute. The literature suggests that the high molecular weight polymeric compounds contributing to the viscosity of the serum also control the consistency of the paste. Foda and McCollum (81), however, reported that pectins did not contribute significantly to the viscosity of tomato juice. Takada and Nelson (82) reported a strong correlation between precipitate weight ratio (PWR), which refers to the ratio of the weight of the precipitate after centrifugation to the initial sample weight, and the Bostwick value and efflux viscosity of the juice. Thakur et al. (83) also reported a strong correlation between PWR value and serum viscosity of the juice (Fig. 2). As described later in this paper, the gross viscosity and serum viscosity play an important role in determining serum separation in processed tomato products. Various factors influencing the consistency of tomato products are described below.

Cultivar

Cultivar used is the most important factor influencing the consistency of tomato products. Each cultivar has a different chemical composition, and this in turn
affects the consistency. Tomato juices and pastes made from different cultivars under similar processing conditions have different consistencies (Fig. 3) (79,84). Pear-shaped tomato varieties contain more pectin than round-shaped varieties, resulting in higher viscosity (85). Luh et al. (85) also reported differences in consistency of tomato concentrates made from fruits of different maturity and from different growing sites.

Break Temperature

Temperature during processing greatly influences the consistency of tomato products. Products processed at higher break temperature exhibit higher viscosity due to greater degree of inactivation of the pectolytic enzymes, pectinaglacturonase (PG) and pectin methylesterase (PME) (35,79,80,83,84,86–95). Thakur et al. (83), and Luh and Daoud (93) reported significantly higher values for serum and efflux viscosities of hot-processed tomato juice and paste as compared to the samples processed by cold break. Reverse osmosis processed (concentrated) tomato juice had better color, appearance, and flavor, whereas evaporation-concentrated juice was higher in consistency (96). Porretta et al. (97), however, reported that ultrahigh hydrostatic pressure (UHP) processing of tomato juice also yielded product which, besides being microbiologically stable, had improved viscosity and color properties. Prolonged heating at high temperature causes denaturation of pectin,
leading to reduced consistency. However, high temperature could also lead to high viscosity, due to disruption of cell structure and the consequent increased leaching of pectin from the cell walls. More pectin in the sample will bind more water, leading to high flow resistance (98). The role of pectin in determining the consistency of processed tomato products is discussed in the following section.

Role of Pectin

Pectins are known to influence the consistency of processed fruit products and are an essential component in many of these products. About 80-90% of the 6-7 million kilograms of purified pectin produced annually, is used in the manufacture of jams, jellies, and similar products (99). Usually, purified pectins are used to augment the naturally occurring pectins in fruit products to achieve the desired firmness or consistency (99).

Pectins are structural, cell wall polysaccharides found in all higher plants, and like most other polysaccharides are both polymeric and polydisperse. Fruit tissues are particularly enriched in the pectic substances, with amounts (dry weight basis) ranging from 7% in tomato fruits to 40% in orange pulp (2,100). The two primary components of pectins are polygalacturonic acid, a homopolymer of (1→4) α-D-galacturonic acid (PGA), and the rhamnogalacturonans (RG), which are contorted rod-like heteropolymers of (1→2) α-L-rhamnose-(1→4) α-D-galacturonic acid repeating units. Rhamnogalacturans are primarily responsible for the chemical and structural complexity of the pectic substances (101). The carboxyl
groups in pectins are esterified with methyl alcohol to varying degrees. Low-methoxyl pectins are susceptible to degradation by pectolytic enzymes, especially polygalacturonase. It has been reported that polygalacturonic acids are secreted as methyl esterified compounds, but they are then cleaved by these enzymes (102). Since viscosity is affected by the volume occupied by the molecule or the extent of molecular association in solution, both the molecular weight and degree of esterification will enhance the viscosity of fruit products (103). Pectins contribute to the consistency and texture of the fruit products primarily through their ability to form gels, which are a network of polymer molecules cross-linked to each other in a liquid medium. In pure pectin gels and fruit products this liquid phase is water. The mechanism of gel formation is different in both high-methoxyl (DM 50–80%) and low-methoxyl (DM 25–50%) pectins. High-methoxyl pectins form gels if the pH is below 3.6 and a cosolute is present, typically sucrose at a concentration greater than 55% by weight. Noncovalent forces, that is, hydrogen bonding and hydrophobic interactions are believed to be responsible for gel formation in high-methoxyl pectins. In low-methoxyl pectins, gels are formed in the presence of Ca$^{2+}$ which act as bridges between pairs of carboxyl groups of pectin molecules (104, 105).

In tomato processing, high heat is applied to inactivate pectolytic enzymes, resulting in high viscosity due to higher retention of pectin (Fig. 4). Enzymatic depolymerization of pectin in pulp or serum of tomato product causes a great reduction in the viscosity of the product. Pectolytic enzymes liberated during crushing, however, act very quickly, and 100% retention of pectic substances is not obtained even under the best commercial conditions of rapidly heating the crushed products (106). Furthermore, degradation of pectin by pectolytic enzymes during ripening and between harvest and processing cannot be prevented (83). However, modification of plant gene expression by genetic engineering has made it possible to control the activity of these enzymes in vivo (107–111). The fruits from transgenic plant with an antisense PME gene contain pectin of higher molecular mass and higher degree of methoxylation compared to that of control fruits (111). Juices processed from these fruits show a significant increase in both serum and efflux viscosity, and also have pectin with higher DM and higher molecular mass (83,108,112).

Cell Walls

Cell walls are the principal structural elements, or building blocks, of juice. Consistency depends upon the quantity, quality, shape, degree of subdivision, and character of the cell wall present (78,84,86,113–115). Cell wall concentration in juice is influenced by maturity of tomatoes, native difference in cell wall thickness, type of pre-heat treatment of fresh fruit, and manner of extracting or comminuting tomatoes to form juice. Unheated green tomatoes give juice low in consistency and cell wall content (113,114). Two juice samples with the same amount of cell
walls may differ in consistency due to difference in the configuration or structural arrangements of the cell walls (116). In general, sheet-like or rod-like walls or wall fragments offer more resistance to flow than round-shaped cell walls, causing an increase in consistency of tomato products. Homogenization of juice increases linearity of cell walls, thus increasing consistency (113,114). Pressure of homogenization influences the increase in consistency. Thakur et al. (98) reported an increase in consistency of tomato juice with increase in the pressure of homogenization from 0 to 3000 psi, after which the viscosity became constant (Fig. 5). The pectin content of a cell wall changes its character. Cell walls devoid of pectin are brittle, friable, and less hydrophilic whereas walls permeated with pectin are tacky, resilient, and as stated earlier, capable of binding more water (100,113). Whittenberger and Nutting (114) found cellulose to be the component of tomato cell wall most closely related to juice viscosity. Segur et al. (117) reported that homogenized cellulose wall suspensions were thicker, per unit concentration, than any of the commonly used thickening agents such as starch, pectin, gelatin, methyl cellulose, or sodium alginate. Consistency can also be influenced by the extent of cell wall rupturing (114). Hand et al. (86) found that additional mechanical cell fragmentation by a piston-type homogenizer resulted in an increased consistency of
Figure 5. Effect of homogenization pressure on efflux viscosity (EV) and serum separation (SP) of tomato juice.

tomato juice. Amount of cell rupturing varies with the method of heating (116). Hand et al. (86) obtained a wide range of viscosities by adjusting finishing conditions at a given preheating temperature. The effect of preheating on gross viscosity was attributed, in addition to the preservation of pectin in the serum, to softening of the chopped tomatoes prior to finishing.

Screen Size and Speed of Blades in Pulper/Finisher

Screen size and blade speed are important factors in controlling the gross viscosity of tomato juice. Nommhoring and Tansakul (25) reported a lower consistency of tomato juice and puree for screen sizes of 0.5 mm (0.019 in.) and 1.5 mm (0.059 in.) than for 1.0 mm (0.039 in.) at any given speed of blades. They also reported that at any given screen size, higher blade speeds resulted in better consistency of tomato juice and puree. Screen size affects the gross viscosity of tomato juice in two different manners. One is by enhancing viscosity due to the large surface area of small particles and the other is by diminishing the viscosity due to exclusion of large particles (118). York et al. (119) reported that in batches with a high percentage of well-colored fruits, controlled damage to tomato fruits resulted in an increase in insoluble solids, thus tending to increase consistency. Hand et al. (86)
found that variation in speed of the paddle in the finisher results in a wide range of gross viscosity regardless of preheating temperature.

Electrolytes

Electrolytes influence the viscosity of tomato juice by keeping the cell wall in suspension. Viscosity of tomato juice is kept at a relatively low level by the presence of naturally occurring and added electrolytes. Removal of naturally occurring electrolytes including soluble pectins, organic acids, and mineral salts may cause the remaining fraction of juice to thicken to a semigel (114). Cell walls bear electric charges and the charges exhibit their maximum effect in the absence of soluble electrolytes. The walls swell, bind more water, and promote high viscosity. Whittemberger and Nutting (113,114) reported that addition of 0.2% NaCl and CaCl₂ to washed cell wall material dampens the charge considerably, causing decreased consistency in the juice. Dougherty and Nelson (120), however, did not observe this phenomenon in whole tomato juice. Many authors (121–123) have reported that addition of NaCl decreases the viscosity of dilute pectic substances. NaCl decreases the charge on the pectin molecule, thus allowing formation of parallel dimers and trimers as well as increases in molecular folds in pectin molecules. It could also reduce hydrogen bonding, leading to decreased consistency (120).

Pectin–Protein Interactions

Tomato juice is a complex mixture of carbohydrates, proteins, pigments, organic acids, and minerals. Interaction between these molecules, especially pectin and proteins, influences the consistency of tomato juice by forming a reversible electrostatic complex (124). The complex formation is pH dependent. The maximum juice viscosity is reached between pH 4.0 and 4.5 due to maximum pectin–protein interaction at this pH range (124). Tomato puree diluted from higher solids such as 20° Brix, however, does not show a change in consistency with changing pH because prolonged heating during concentration of tomato juice may denature the protein and stabilize its complex with pectin, resulting in an irreversible complex (124). Many factors including processing conditions, pH, and degree of esterification in pectin may influence the nature of these interactions. Beresovsky et al. (125) studied the effect of pulp particle interactions on the viscosity of the juice. They found that the higher the value of interaction index, the higher the viscosity. The index decreases during concentration of tomato juice and is increased by homogenization. Thakur et al. (98) reported the positive effect of homogenization, particularly at higher pressure, on the viscosity of tomato juice. Enzymatic degradation of pectin decreases the interaction index and hence the viscosity of the juice. Foda and McCollum (81), however, reported that degradation of proteins of tomato juice with pronase causes relatively small losses of viscosity.
Fruit Solids

Tomato solids are an important quality factor emphasized by the tomato-processing industry (3). They influence the final yield, consistency, and overall quality of the finished product. Thus, high solids in fruits are desirable because making concentrates to a specified solid level with high-solid tomatoes provides greater product yield and also requires less water evaporation, reducing the cost.

As regards to crop yield, there is an inverse relationship between soluble solids and yields. Varieties with high yield tend to have lower soluble solids and vice versa. Fruit soluble solids account for approximately 75% of the total dry weight of ripe tomato fruits (126). Generally, varieties with high sugar content have high solid levels. In cultivated varieties, soluble solids range from 4% to 6%. Sugar content varies with the cultivar and fruit yield per acre. Even within the same cultivar, there can be variation in sugar due to difference in horticultural practices and seasonal variation (3). Due to large differences in the soluble solid content of cultivated and wild-type tomato species, interspecies breeding has been used to improve the levels of solids in the cultivated species (127,128). Tomato lines with soluble solids over 9% have now been released and some scientists believe that tomatoes with solids as high as 15% are possible or are on the horizon (3). Increase in soluble solids increases the consistency of tomato juice (Fig. 6).

Growing and later processing conditions influence the concentration of sugar in the fruit and processed tomato products. For example, fruits grown in bright

![Figure 6. Effect of tomato juice concentration on consistency. (Modified from Ref. 31.)](image)
sunlight in summer contain more sugar compared to hothouse tomatoes grown during the winter months (129,130). During processing, heating of tomato products results in loss of sugar due to caramelization, Maillard reactions, and the formation of 5-hydroxymethylfurfural in the acid medium upon loss of H₂O (1). El-Miladi et al. (7) reported a total sugar loss of 16% in processed tomato juice, losses being the same for both glucose and fructose. Alpari (131) found 5% loss of sugar during manufacture of powdered tomato from puree. Gancedo and Luh (132), however, reported no effect of break temperature on soluble sugar content of juice made from UC 82B tomatoes.

Due to the time-consuming measurements needed to determine total solid contents, other components of the total solids (soluble solids) are measured as degree Brix. To measure soluble solids (degree Brix), a refractometer is used. The refractometer measures the refractive index of the solution. As light passes from one medium, such as air, into another medium, such as an aqueous solution, the light rays are refracted (bent), and the refractive index \( \mu \) of the solution is given by the relationship:

\[
\mu = \frac{\sin i}{\sin r}
\]

where \( i \) is the angle of incidence and \( r \) is the angle of refraction. The refractive index of a solution is dependent on the concentration and temperature of the material, and on the wavelength of the light, which is kept constant for the refractometer. In practice, refractometers are calibrated directly in percentage of sugar. If a material expands when heated, it will become less dense and the refractive index will decrease, and vice versa.

**Serum Separation (Degree of Settlement)**

Serum separation, or degree of settlement, is a significant problem in maintaining the quality of tomato products. The homogeneous appearance of tomato juice depends on the stable distribution of insoluble particles throughout the serum column. The quality and quantity of insoluble material present influence the serum separation in tomato juice. Serum separation in tomato products can occur in two ways: (i) if there is too much liquid for a given concentration of insoluble particles which cannot fill the volume of the liquid column; (ii) through reduction in the volume of precipitate due to gradual collapse under gravity during storage of the product (94). There is an inverse relationship between the serum separation and viscosity of the product. As a general rule, the product with highest viscosity exhibits minimum serum separation. Serum separation in juice is caused by packing of suspended particles into a smaller volume rather than by simple sedimentation in the serum (91). A number of factors influence serum separation in tomato products, as described below.
Break Temperature

Variation in processing conditions cause a wide difference in the degree of settling of tomato products. Hot-break-processed juice shows less serum separation than cold-processed juice. This effect may be due to better retention of pectins in the juice (83). Robinson et al. (91), however, reported that amount of pectin did not have a major effect on the degree of settling in tomato juice. They reported that higher amounts of crude fiber reduced the serum separation. Shomer et al. (94) also found cellulosic material more important than pectic substance in reducing serum separation in tomato juice. They argued that the degradation of pectin leads to partial dispersion of the microfibrillar system in the wall. Expansion of the microfibrillar system and retention of its ability to withstand collapse under gravity stress prevents serum separation in tomato products.

Homogenization

Homogenization causes a marked increase in the volume of particles due to rupture of the cellular envelope. The ruptured cells do not settle as compactly as the intact cell (86), leading to reduced serum separation in homogenized juice (91, 98). Serum separation decreases as the pressure of homogenization increases from 0 to 3000 psi, after which it becomes constant (Fig. 5). Mechanical disintegration releases microfibrils from the torn edges of the wall fragments, increases their effective dispersion, and prevents efficient packing into a precipitate of low volume (94). The effect of homogenization on the shape of the particles is more important than the decrease in their size in reducing serum separation in homogenized juice (91).

Different workers proposed different methods to measure the serum-holding capacity of tomato products. Kertesz and Locoti (133) and McColloch et al. (80) measured the rate of filtration through a shark skin filter paper. The volume of filtrate at the end of 30 min was used as measurement of the tendency to hold the liquid portion. Nelson et al. (89) developed a blotter test where a small quantity of the sample is placed in the center of filter paper previously marked with concentric circles. The distance that the serum seeps across the paper in a given time is the measure of serum separation. Tendency of suspended particles to settle over time has also been used to measure serum separation in tomato products (91, 134). Robinson et al. (91) reported a procedure to measure serum separation during storage of tomato products by recording the distance between the top of the juice and the top of the mass of suspended solids in a tall-necked glass bottle. But all these methods are time consuming and not highly accurate. Nelson et al. (135) developed a quick and reliable test using a 42-mesh stainless steel cone of 60° and approximately 10 cm side length. The sample is put into the cone and the amount of serum drained in a given time is a measure of the serum-holding capacity of the product.
Total Acidity and pH

Acid concentration and pH are important quality and processing characteristics of tomatoes (136). In addition to flavor and consistency, they influence the processing time and temperature of the products. Higher pH values necessitate longer processing times which adversely affect the product quality. Practically all foods contain an acid or a mixture of acids which may be either present naturally, produced by microorganisms, or added to the food during processing. Both [H+] and potential acidity contribute to tartness in the food (136). Generally, the acid concentration in tomatoes increases during development, reaching maximum near incipient color; thereafter, the acid content decreases (12). The average acidity of processing tomatoes is about 0.35% expressed as citric acid. Presently, tomatoes or tomato products may be stored aseptically in drums, bags in boxes, or large tanks for later use. In such a system the more acidic a product is, the easier it is to control the asepsis (119). The pH should be lower than 4.4 to avoid problems with thermophilic organisms (136). The pH influences the consistency of tomato products by modifying the total pectin content and pectin characteristics. High-consistency juice, prepared by acidification of the tomatoes to pH 2.5 or below during breaking and heating, contains a larger amount of pectin and a larger proportion of highly esterified pectin than juices prepared at the natural pH of the tomatoes. Low pH may affect consistency by inhibiting pectolytic enzymes and by increasing the extraction of pectic and other high molecular weight tomato constituents (137). Dougherty and Nelson (119) reported that when tomato juice was acidified to various pH levels, sealed in cans, and stored for 3 months, pH had a highly significant effect on consistency of the product. As pH decreased below 4.0, consistency showed a significant decline through pH 2.0.

Total acidity and pH in tomato are not always inversely related. In some varieties, both values are relatively high (136-139). Phosphorous concentration of the fruit (due to its buffering capacity) is an important factor in the poor relationship between pH and acidity in tomato fruits. Decreased phosphorous in the fruit helps to alleviate the high-pH problem in low-acid lines (140). The presence of potassium in the growing medium increases titratable acidity due to its effect on free acid in tomato fruits (17,141). Acidity of the tomato is also increased by nitrogen in the soil. Stevens (10) found wide variations in the [H+]/titratable acidity ratio among 55 divergents.

Processing conditions (hot and cold break) are reported to influence the pH and acidity of processed tomato products. Hot-processed juice has lower titratable acidity and higher pH compared to cold-processed juice (93). The differences in titratable acidity can be attributed to the activity of the pectolytic enzymes in the cold-break juice which produce acidic breakdown products from pectin (142). Sherkat and Luh (34) reported higher acidity and low pH in tomato products processed at 64.4°C (148°F) and 77.2°C (171°F) compared to those processed at 100°C (212°F) and 104.4°C (220°F). They attributed this to the formation of pectic,
oligouronic, and galacturonic acids from pectic material due to the activation of pectolytic enzymes at the lower temperatures. Gancedo and Luh (132) also reported lower acidity and higher pH in juice processed at high temperature. Loss of volatile acids and carbon dioxide at higher temperature may also contribute to the differences in acidity between the samples. Changes in acid composition of tomato products before and after heating have been reported by some workers (61,143-145). The reports, however, are conflicting. El-Miladi et al. (143) reported that α-ketoglutaric acid decreased while citric acid increased with processing. Hamdy and Gould (144), on the other hand, found the opposite in their study. Temperature of processing also affects the acid composition of tomato products. Juice processed by macerating fruits at 65°C contained high amounts of oxalic acids while the product with a break temperature of 104°C contained no oxalic acid due to heat inactivation of the Kreb cycle enzyme at high temperature (144). Wiese and Dalmossa (32) also reported increases in organic acids (lactic acid, malic acid, citric acid, and pyrocarboxylic acid) after processing of tomato juice. Villari et al. (33), however, reported decreases in organic acids with increased storage time and temperature of tomato paste. They also reported a decrease in pH and increase in the acidity during storage of tomato juice.

Nutritive Value

As is evident from the composition and the amount consumed, tomato is the most important crop in terms of total vegetable-derived minerals and vitamins in the U.S. diet. Carotenoids are the coloring pigments of tomato fruit and processed tomato products, lycopene being the major carotenoid. Carotenoids are important not only from the color point of view but also as a rich source of vitamin A. Recently they have been found effective in preventing cancer (146-149). Lycopene, though devoid of any vitamin activity, contributes to the antioxidative defense mechanism of the organisms that consume it (150,151). In vitro studies have proved that some naturally occurring and synthetic carotenoids without provitamin A activity are superior to β-carotene in quenching singlet oxygen (152, 153). Lycopene was found to be especially effective (152,154). Lycopene contributes to the same extent or even more than β-carotene to total carotenoids in human tissues (155,156). Absorption of tomato carotenoids in the body has been reported to be influenced by the processing conditions of tomato products. Stahl and Sies (150) reported that uptake of lycopene by humans is greater from heat-processed (heated with 1% corn oil) than from unprocessed tomato juice. A possible mechanism for this may involve the thermally induced rupture of cell walls accompanied by release of lycopene from cells, heat-improved extraction of lycopene into lipophilic corn oil as a vehicle, or a combination of several other factors. Sakamoto et al. (157) reported that continual ingestion of tomato juice is effective in raising serum levels of lycopene and β-carotene. Increase in levels of carotenoids in serum
by tomato juice did not induce an increase in the levels of serum lipids. In addition, tomato products are a rich source of minerals and various acids.

CONCLUSIONS

The quality of processed tomato products is highly variable, and utmost care should be taken in selecting the cultivar and in controlling both the growing and the processing conditions. There can be a wide difference in the quality of processed products even from the same cultivar if the growing and processing conditions are different. Processing conditions have a great influence on the overall quality of the final product. For example, a different range of viscosities can be obtained by simply changing the blade speed of a finisher. Processing at lower temperature allows better retention of color and aroma; however, the product may separate on standing. On the other hand, high-temperature processing gives a more stable product with high consistency, but changes the color and aroma of the products. In short, a number of factors influence the quality of the final processed tomato products, and a balance has to be made between various factors to obtain a product with desirable quality attributes.

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