Understanding Tomato Peelability
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Abstract: Approximately 75% of all tomatoes in the United States are consumed as processed and 25% as fresh. One of the first steps during processing involves removal of the peel and, unfortunately, more than 25% of the fruits (as measured by total weight) can be lost due to overpeeling. Additionally, conventional peeling applications have a negative environmental impact. Given the great potential economic benefits, many scientists have conducted research to attempt optimizing or predicting peeling performance when processing tomatoes. The literature regarding tomato peelability is contradictory in many cases; and several topics have been subject to ample debate over the years. Divergent conclusions are probably not due to faulty investigations, but rather to the extreme variability found among tomato cultivars, the effect of growing seasons, and maybe even the effect of climatic conditions on the day of harvest or during transportation to the processing plants. This review provides an in-depth background needed for a better understanding of tomato physiology, maturation, and composition, as these could possibly influence the ease of peeling or “peelability.” The research studies directly involved with peeling tomatoes and predicting peelability are discussed in this paper as well. Different peeling methods, peeling grading scales, and fruit tagging procedures are presented, as well as experiments evaluating the effect that fruit defects, maturity, growing conditions, and other factors can have on the ease of peeling. Novel approaches for peelability prediction by means of spectroscopic and magnetic resonance technology are also discussed in this review.

Keywords: peelability, peeling methods, peeling performance, peelability prediction, tomato

Introduction
Judging from their humble appearance, it would be difficult to guess that tomatoes (Lycopersicon esculentum) are indeed the moving force behind a huge industry. According to the statistics for 2012, gross production values of tomatoes in the U.S. and the world were approximately 5 and 60 billion dollars, respectively (FAOSTAT 2015). In addition to the economic impact, tomatoes have numerous health benefits. They are an important dietary source of vitamin C (Abushita and others 1997) and the potent antioxidant lycopene (accounting for up to 50% of its estimated total daily intake) (Agarwal and Rao 2000), and their consumption is associated, among other things, with decreased risk of several types of cancer (Rao and Agarwal 1998; Giovannucci 1999) and cardiovascular disease (Arab and Steck 2000; Sesso and others 2003). The perception society has had of tomatoes has not always been the same. Originally from South America, the plant was introduced in Europe at mid-16th century, where it remained merely an ornamental fixture, admired for the beauty of its fruits but considered as poisonous. It was not until the 18th century when eating tomatoes became a common practice. By that time it was also reintroduced to America from Europe, being eventually promoted as a source of vitamins to enrich the diets among the poor (Jones 2007). Since then, tomatoes have continued to grow in importance, finally becoming a staple in the diets of many worldwide cuisines.

In today’s world, tomatoes are used for 2 different purposes: fresh consumption and processing. About 75% of the tomatoes in the U.S. are processed prior to their consumption and usually peeling those tomatoes is one of the first steps applied in the industry. Due to the lack of standard peeling protocol, which could be applied to all tomatoes, there is often more than 25% of total fruit weight loss as a result of overpeeling as opposed to only 7% to 10% lost from optimum peeling (Barringer and others 2008). There have been many studies in the literature on tomato peelability and there is still a need for optimization of the tomato peeling process. Given this review’s emphasis on tomato peelability, it is necessary to start with an overview of the tomato fruit’s development, its maturation/ripening process, and the components in the fruit that are relevant during the peeling process. Then follows a section on the description of the tomato industry in the U.S. Consequently, previous studies on peeling methods, lye diffusion, quantifying peeling performance, fruit tagging performance, peeling aids used, physiognomy, the effect of tomato defects, cuticle, maturity, and developmental conditions, and, finally, postharvest handling as related to peeling will be exhaustively discussed. Studies on modern methods used to predict tomato peelability will also be presented.

Fruit Development
In general terms, the growth pattern of tomato fruits can be described as sigmoidal (Ho and Hewitt 1986). As seen in Figure 1

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Tomatoes are climacteric fruits since a peak in respiration and ripening start at the blossom end and progressively advance towards the stem (Catala and others 2000). There is an initial period of slow growth after fruit set and cell division (stage I), which is followed by 3 to 5 wk of rapid fruit expansion (stages II and III). The growth rate then decreases throughout the immature and mature green stages. Although most of the fruit weight is accumulated by the end of the mature green stage (IV), there is a subsequent period of slow growth where intensive metabolic changes occur. Color progressively develops, going from yellow to orange and, eventually, to red (Ho and Hewitt 1986).

Tomatoes are climacteric fruits since a peak in respiration and an ethylene burst accompanies their ripening. It has been reported that the ripening process starts on a section of a fruit and then gradually spreads to adjacent regions as the ethylene diffuses from cell to cell (Alexander and Grierson 2002). External color development and tissue softening, attributes frequently associated with ripening (Hall 1964), are both usually first observed at the blossom end (Brecht 1985; Kojima and others 1991) with a gradual progression towards the stem area (Figure 2).

The conspicuous changes observed during ripening suggest that the intense metabolic reactions occurring throughout this period are originated at the blossom end of the fruit and then extend towards the stem. This progression seems to be gradual and heterogeneous, given that different points along the tomato’s equator can differ in coloration, even at the same points of the developmental stage. Tomato development entails a myriad of changes, not only in appearance, but also in chemical composition, cell structure, and respiration. A very thorough description of the whole process can be found in the book “Tomato Crop” by Grierson and Kader (1986). The following sections will focus on changes occurring at the outermost layers of the fruits, especially the cuticle and cuticular waxes which are in direct contact with the exterior.

**Cuticle**

Water is the most important constituent of tomato fruits (Davies and Hobson 1981). In order to avoid uncontrolled moisture loss, plants have developed a cuticle, an efficient external barrier that protects them against the exigencies of the environment. Besides minimizing loss of water and other substances from internal tissues, the cuticle protects against chemical, physical, and biological threats (Jeffree 2006).

With a thickness ranging from 4 to 10 µm (Wilson and Sterling 1976), the cuticular membrane is basically composed of waxes that are embedded (intracuticular) or deposited on the surface (epicuticular) of a cutin matrix. Cutin can be described as an insoluble (López-Casado and others 2007) and amorphous biopolymer mainly formed by hydroxylated and epoxy-hydroxylated C_{16} and C_{18} esterified fatty acids (Heredia 2003). Moisture escapes through the cuticle by means of a simple diffusion process based on the chemical potential of water (Riederer and Schreiber 2001). Two pathways have been proposed to explain said mechanism (Schönherr 2000). The “nonpolar” pathway involves migration through the amorphous phase of cuticular waxes. The “polar” pathway implies the existence of hydrophilic pores that offer a route for watersoluble organic compounds and inorganic ions (Schönherr 2000). Both pathways are parallel and independent.

There has been considerable debate on the existence of polar pores. The work of Markus Riederer stands out in this area. After concluding that the bulk of water diffuses across the lipophilic barrier in the form of single molecules, thanks to their small size and lack of charge (Riederer and Schreiber 2001), Riederer later reached a different conclusion. Deeper insight into the nature and the temperature-dependent behavior of the polar pathway indicated that water preferentially permeates through it, more specifically along polysaccharide strands that cross the cuticle. The later explanation suggests that there is a critical temperature at which swelling occurs, which opens up new and “stiffer” regions of the polysaccharide net thus enhancing water permeance (Riederer 2006). Probably more work will be necessary to finalize this issue.

Besides its role as a barrier, the cuticle may also help preserve firmness on tomato fruits. Softening is generally attributed mainly to the internal disassembly of polysaccharide networks in the primary cell wall and middle lamella (Rose and others 2003). However, Saladié and others (2007) have proposed a model in which the cuticle’s specific compositional and/or ultrastructural characteristics can affect the softening of intact tomato fruits both directly, by providing physical support, and indirectly by regulation of the water status.

Regarding the cuticle’s development, it steadily continues during fruit enlargement, achieving a 20-fold increase in membrane thickness from the immature green to the postclimacteric stages. One of the main contributors to this expansion is the outstanding increase of cutin that grows in weight up to 80% of the cuticle.
at the mature green stage (Baker and others 1982). The increase in cuticular membrane does not occur in a linear fashion (Bargel and Neinhuis 2005), purportedly due to the sigmoidal growth pattern, where rapid expansion stretches the exocarp constituents to a great extent. Additionally, it has been proposed (Domínguez and others 2008) that different cultivars may synthesize cuticule at different rates. According to this theory, medium/large tomatoes would accumulate cuticle material slowly, whereas smaller varieties, such as cherry tomato, would show faster accumulation. Other than cultivar, many factors can affect the formation of the cuticle. Research carried out by Domínguez and others (2008) indicates that environmental conditions prevailing during different stages of physiological development could influence the synthesis of a fruit’s cuticle. Certainly, the possibility of agents such as light, temperature, and relative humidity influencing cuticle development cannot be discarded without careful examination.

Waxes

Gas chromatography paired with mass spectrometry was used to characterize the constituents of a tomato’s surface wax (Bauer and others 2004a). The components were classified into 3 categories. The first fraction was made out of hydrocarbons and aldehydes; the second fraction consisted of n-alkanols, alkanolic acids, sterol, and triterpenols; and the third fraction was composed mainly of naringenin chalcone. Baker and others (1982) elucidated that waxes decline during maturation, going from 12% of the cuticle weight at the small green stage to 3% in mature green fruits. However, Bauer and others (2004b) revealed that, once tomatoes enter the ripening phase, the wax layer increases. By following the progression of 1 tomato cultivar, it was found that the layer thickness was 11.68, 73, and 79 µg/cm² for green, green-orange, red, and mature red stages, respectively. The strong rise was mainly due to the formation of fraction 3 (naringenin chalcone) purportedly. Although it was not present at the green stage, naringenin chalcone later grew to become the main component in the wax layer. Very interestingly, when the wax composition of 26 different cultivars was analyzed, 3 cultivars had no detectable levels of this chalcone at the red ripe stage.

There is substantial evidence that epicuticular and intracuticular waxes have divergent chemical composition. Epicuticular films are thought to be formed mainly by very-long-chain aliphatics; intracuticular extracts, on the other hand, have been reported to also contain high proportions of pentacyclic triterpenoids and “short series” fatty acids (Baker and others 1982; Vogg and others 2004).

Water permeability of the cuticle has not been correlated with its thickness or wax coverage (Riederer and Schreiber 2001; Leide and others 2007). Studies suggest that wax quality, rather than quantity, is the 1 determining barrier properties of tomato fruits. Experiments carried out using tomato mutants have shown that a decrease of intracuticular aliphatics, as well as a decrease of n-alkanes (chain lengths > C₂₈) with concomitant increase in cyclic triterpenoids, significantly enhances cuticule water permeability. Therefore, the main portion of the transpiration barrier could be located in the intracuticular realm (Vogg and others 2004; Leide and others 2007).

Published reviews on the workings of cuticle permeability highlight the importance of assessing the cuticular barrier based on its chemical composition. Inferences drawn from the cuticular thickness or the measurable amount of waxes are deemed unlikely to translate into accurate predictions of permeability (Kestiens and others 2006).

Cutticular phenolics

Flavonoids are the largest and the most studied group of plant phenols found in nature (King and Young 1999). In plants they are secondary metabolites contributing to functions such as signaling, fertility, and protection against biotic and abiotic stresses (Weisshaar and Jenkins 1998). They also provide color to flowers, fruits, and leaves (Kähkönen and others 1999) and are reported to have various biological benefits due to their antioxidant capacity (Dugas and others 2000).

The phenolic content of tomato cuticles changes over time. It has been found to increase throughout fruit expansion, and substantially more during ripening up to the point when it becomes the major wax fraction of ripe fruits (Baker and others 1982). Despite representing less than 5% of the surface extracts obtained from green fruits, it accounts for 7% to 14% of the extracts at the onset of climacteric and 21% to 26% during postclimacteric stages (Hunt and Baker 1980).

Early studies reported the predominance of 2 phenolics on the cuticle of ripe tomato fruits, naringenin and naringenin chalcone (Hunt and Baker 1980; Baker and others 1982). However, a subsequent study that used highly sensitive instrumentation concluded that the previously reported presence of naringenin was most likely an artifact, based on the fact that naringenin can be readily formed from its chalcone under experimental conditions. It took only 2 h in a methanolic solution at 50 °C for all the chalcone in a sample to turn into naringenin (Bauer and others 2004a). A later study on Micro-Tom tomatoes (Iijima and others 2008) using methanol extraction (no indication of the temperature was given) found naringenin conjugates, but it was concluded that naringenin chalcone was the major chalcone in tomato fruit. Overall, studies agree that naringenin chalcone is a component of great importance among cuticular phenolics.

The major stores of flavanones and chalcones are in a tomato’s peel (Iijima and others 2008). Based on their rate of accumulation, these phenolics can be classified in 3 groups. The first group (naringenin chalcone and eriodictyol chalcone) reaches its highest concentration at the breaker stage and gradually decreases during ripening. The second group (naringenin derivatives) peaks at the turning stage and decreases at the red stage. A third group of metabolites, on the other hand, increases during ripening and reaches its maximum levels at the red stage. Mapping of putative modification pathways suggests that those compounds found in the first 2 groups are precursors for those that increase at the red stage, indicating that chalcones and flavanones undergo sequential modification during ripening (Iijima and others 2008).

There is evidence (Laguna and others 1999) that cuticular flavonoids on ripe tomato fruits (such as naringenin chalcone) have high affinity for cutin constituents, but no affinity at all for cuticular waxes; therefore, they accumulate on the cuticular domain forming clusters with very low mobility and high molecular cohesion. In doing so, they may reduce available hydroxyl groups in the cutin matrix and/or decrease volume within the network (Bargel and Neinhuis 2005). Such behavior could, in turn, affect the rigidity of the cuticular membrane. Recent research (López-Casado and others 2007; España and others 2014) on the biomechanics of isolated tomato fruit cuticle points at phenolics as the main candidates to explain the increased rigidity that typically occurs in this tissue from the mature green to the red. 
The Tomato Industry in the United States

In the U.S. there are 2 distinct industries that commercialize tomatoes; one is focused on fruits for fresh consumption and the other deals with tomatoes for processing. The trades differ considerably in their production practices, breeding objectives, and target markets. Very detailed information about the current state of both industries is provided by the U.S. Dept. of Agriculture (USDA) Economic Research Service website (Economic Research Service 2012).

Tomatoes rank fourth in terms of fresh vegetable consumption in the U.S. Various population groups with vegetable-intensive diets and an overall increased interest on health and nutrition have contributed to boost per capita utilization of the fruits. Fresh-market tomatoes are produced in every state of the nation, with California and Florida accounting for almost 66% of the total acreage. The harvest peaks in spring and is the lowest from August to September; however, the fruits are available all year long thanks to imports that supplement national production. Retail prices tend to be more elevated than those of processing varieties due to higher production costs and market uncertainty (Economic Research Service 2012).

Although the fresh market accounts for a good portion of the tomatoes consumed in the U.S., 75% is now consumed in a variety of processed forms, mainly because of the rising popularity of pizza, pasta, and salsas. The most fundamental differences among fresh-market and processing tomato industries are:

- Fresh-market tomatoes are handpicked, while processing tomatoes are machine-harvested. All tomatoes were collected by hand before 1964, but after labor shortages that year mechanization was quickly adopted (Brandt and French 1983).
- Processing tomatoes are harvested when red ripe, but most fresh-market tomatoes while still green (California Tomato Grower’s Assoc. Inc. 2015).
- Once out of the field, fresh-market tomatoes are allowed to mature over time. Most mature green fresh-market tomatoes are artificially ripened by controlled exposure to ethylene gas. Processing tomatoes are used immediately, usually within the same day (California Tomato Grower’s Assoc. Inc. 2015).
- Processing tomato growers establish business contracts with processing firms. Fresh tomatoes are sold on the open market (Economic Research Service 2012).
- Processing cultivars have been selectively bred for over 50 y to develop characteristics that noticeably differentiate them from fresh-market varieties. They are bred for higher Brix and stronger peels, which are necessary to resist the rigors of mechanized harvesting, and they also produce high-viscosity pastes (Garcia and others 2006).

As it can be seen, there are striking differences between the 2 industries, not only in the commerce chain, but also in those traits that are considered desirable for tomatoes in each market. The remainder of this review paper will focus on processing tomatoes.

Peelability Studies

As stated above, 75% of the tomatoes consumed in the United States have undergone some degree of processing (Economic Research Service 2012). Most of the time, an initial peeling step is required (Das and others 1995). Unfortunately, the peeling performances found among and within cultivars are highly unpredictable, and it is not possible to preestablish a standard peeling protocol to achieve even peeling of all the fruits. The overall uncertainty associated with the step leads to losses typically surpassing 25% of the total fruit weight (Barringer and others 2008).

An optimum peeling should remove only the tomato epidermis, generating a loss between 7% and 10% of the total fruit weight (Barringer and others 2008). This scenario would be ideal both for nutritional and commercial reasons. When the peeling reaches deeper regions of the exocarp, it can remove what is known as the “red layer” (Garcia and Barrett 2006a); this outer section contains most of the vitamin C (Holman 1956) and lycopene (Juven and others 1969) found in the fruits. Additionally, since lycopene is greatly responsible for the red color of tomatoes (Juven and others 1969), the absence of this layer in turn yields tomato products of poor appearance.

Products such as whole peeled, diced, and crushed tomatoes are commercialized with greater profit margins than tomato paste (Garcia and Barrett 2006a). However, these premium products should ideally retain high-quality color, uniformity, and appearance. Currently, there are no reliable guidelines for processors to decide whether to send tomato loads to paste or higher value products (Barrett 2001). The decision could be based on historical knowledge of the cultivar and grower, or on visual inspection of the incoming loads (Garcia and Barrett 2006a). A load’s frequency of defects may also be considered, as there are many tomato defects that affect the value of peeled tomatoes, but are not detrimental for the production of juice or paste (Barrett and others 2006). Many tomato processors can attest to the fact that the criteria currently used to assess incoming product performance is in need of serious scientific improvement.

Peeling methods

In principle, industrial peeling of tomatoes involves destroying a thin layer of tissue just below the cuticle with minimal injury to the cuticle itself (Juven and others 1969). The cuticle is thus not eliminated, but rather loosened, and needs to be removed. Skin removal is performed with mechanical peel eliminators such as brushes or rubber discs. The use of tumbling high-pressure jet rotary washers that promote fruits to rub together while water jets remove material from the surface, has also been reported to be effective (Hart and others 1974; Rutledge 1991).

There are many methods that can be used to detach the peel from tomato fruits. The most prominently found in the literature include peeling by pressurized steam and lye (NaOH). Other techniques such as enzymatic, ohmic, power-ultrasound, infrared, and freeze-peeling have also been studied but are not yet favored by the industry due to low throughput, high cost, and/or unease with a new technology (Thomas and others 1976; Das and Barringer 2006; Li and others 2009; Rock and others 2012; Wang and others 2014; Pan and others 2015; Wongsa-Ngsari and Sastry 2015).

Lye-peeling, a commonly used tomato peeling method, requires the use of NaOH (8 to 25 g/100 g water) and elevated temperatures (60 to above 100 °C). Very high pH effluent (above 13) cannot be released to either natural water or soil directly and requires prior acid treatment for neutralization, since an increase in soil pH does not allow subsequent efficient crop and bacterial growth (Wongsa-Ngsari and Sastry 2015). Back in 2006, it was reported that 70% of the processing tomatoes in California were peeled with steam or hot water blanching, as an alternative
obeying to strict environmental laws and regulations, whereas 30% were peeled with lye (Garcia and Barrett 2006b). When compared to lye peeling, the main advantage of steam is that it is being safer for the environment. Beyond purely altruistic implications, steam-peeling avoids problems of high salt content in wastewater whose disposal can be costly (Garcia and Barrett 2006b; Li and others 2009). Steam-peeling is also reported to have significantly higher proportional recovery, but, unfortunately, the final product quality may not be as good. The use of steam results in poorer skin detachment and less defect removal, which are major downsides for industry objectives. Also, despite allegations that steam-peeling improves surface color due to increased retention of mesocarp, experimental data have not always been conclusive (Thomas and others 1976; Schlimme and others 1984).

A study that assessed different levels of steam as an option for lye-peeling (Garcia and Barrett 2006b) concluded that low steam pressures were insufficient to adequately peel the cultivars tested, and, although higher pressures were more efficient at peel removal, the considerable loss in firmness observed across treatments was accentuated with the use of the more severe conditions. During this particular study, the efficiency of a lye-peeling technique was observed even at the mildest treatment, and smaller variability in peelability was also recorded.

Among the various food processing systems the ones which require less energy, less water, better wastewater management, and minimal chemical contamination of the environment have become more popular since they are more sustainable (Pan and others 2015). Therefore, as opposed to steam- and lye-peeling, which have been popular since the 1940s in the tomato industry, there are studies now aiming at developing new systems which can minimize water and the chemical usage and reduce the cost and the effluents (Pan and others 2015). Peeling technique utilizing ohmic heating was investigated to solve the problems associated with the traditional tomato peeling methods. Wongsa-Ngasri and Sastry (2015) ohmically heated tomato samples in NaCl solutions and tried different conditions. They reported that field strength, NaCl concentration, initial temperature, and fruit concentrations were found to be important for tomato peelability. Ohmic peeling of about 1 min showed great potential and similar efficacy to lye-peeling without causing environmental problems. However, this study was conducted on a pilot-scale and it needs to be optimized and scaled-up for commercial applications.

Another novel approach under study as a replacement for lye-peeling of tomatoes is infrared (IR) peeling (Li and others 2009, 2014a,b; Pan and others 2009, 2015; Li and Pan 2013a,b). This “dry peeling” method exposes the fruits to an IR radiation source. The energy (nonionizing radiation) with surface heating characteristics has a relatively low penetration depth. The heat created only affects a thin layer of tomato surface but it is enough to loosen the skins with minimum changes in the inner part of the tomato. When evaluated, IR methods produced similar peelability, less peeling loss, and similar or slightly firmer texture than lye-peeling (Li and others 2009). Pan and others (2015) developed a pilot-scale infrared dry-peeling system for tomatoes. The system they designed and constructed included 3 sections: infrared-heating, vacuum, and pinch-roller sections. The researchers evaluated the performance of the system using different tomato cultivars and sizes. They achieved better peeling performance with smaller tomatoes, since a higher surface temperature was obtained. However, the texture of peeled tomatoes became worse as IR heating time was extended. The final peeled tomato samples carried desirable quality properties with high firmness and surface integrity. In addition to being a chemical and water-free process, tomato skins obtained after IR-peeling can be utilized as byproducts. IR-peeled tomatoes showed lower peeling loss, thinner peeled-off skin, and better texture than lye-peeled tomatoes while providing similar ease of peeling. The technology is still in its early stages and there is not much information about estimated implementation costs. However, if a method is developed that delivers IR radiation homogeneously to the tomato surface in a rapid, high-throughput manner; if that method is able to achieve similar results to lye peeling; and if the cost of its industrial use offers an advantage compared to the application of NaOH (including the cost of waste water treatment), then IR-peeling would have a good potential as an alternative to lye.

Regarding the effect of peeling methods on the nutritional content of tomatoes, it is believed that there is a loss of nutritional components (such as lycopene, β-carotene, ascorbic acid, phenolics, and thiamin) that varies among cultivars (Vinha and others 2014), and such a decrease has been hypothesized to be due to processing itself, regardless of the peeling method chosen (Saldana and others 1978; Thomas and others 1978). However, as Martinez-Huélamo and others (2015) reported, mechanical and thermal treatments applied to tomatoes during the manufacturing of tomato products such as tomato sauce can enhance the release of bioactive compounds from the food matrix and therefore increase the bioavailability. Additional detailed explanations of traditional and alternative tomato peeling methods are readily available in the literature (Garcia and Barrett 2006b; Yaniga 2007; Rock and others 2012) and are not the focus of this review paper.

**Lye diffusion**

The use of lye-peeling is on the rise in important processing regions in the U.S. (Garcia and Barrett 2006b). If the relationships among the different parameters that determine NaOH diffusion were understood, it would be possible to better control the degree of lye penetration and, consequently, the extent of peeling in order to avoid unnecessary losses. In this regard, several efforts have been made.

First of all, it is necessary to understand how NaOH detaches a tomato’s skin. Floros and Chinman (1989) proposed a model where the hot lye solution first dissolves cuticular waxes, then penetrates the skin and continues to diffuse evenly into the fruit. Once inside, the lye breaks down epidermal and hypodermal cells, thereby causing skin separation. By the end of his experiment, the authors calculated the diffusivity of 2 M sodium hydroxide solutions to be $2.0 \times 10^{-8}$ cm$^2$/s through tomato skin at 72 °C. In 1990, it was discovered that when sodium hydroxide for peeling is above a certain baseline concentration (namely $\geq 2$ M NaOH, or 8% NaOH), the diffusivity becomes independent of concentration (Floros and Chinman 1990). This has important applications for the industry, since at concentrations above this threshold, further addition of lye is inconsequential and wasteful. In 1994, Bayindirli (1994) published information indicating that during the lye-peeling of tomatoes the time–temperature correlation is linear, while the time–concentration correlation exponentially decays. As a result, the effect of temperature on peeling efficiency is much higher than the effect of NaOH. Bayindirli advised to first select the temperature desired for peeling and then to optimize the lye concentration. In addition to temperature and lye concentration, the time of exposure affects the efficiency of lye-peeling, with increased times resulting in higher losses. Immersion time has also
a critical effect on fruit firmness; this effect is superior to that exerted by the temperature of the bath (Juven and others 1969).

Some authors have gone to the extent of suggesting ideal combinations of processing parameters that would offer the best peeling results according to their experimental conditions. Juven and others (1969) obtained the highest quality of peeled tomatoes and minimal peeling losses using 18% NaOH at 90 to 95 °C for 20 to 25 s. Bayindirli (1994) suggested 9% NaOH at 90 °C for 60 s. Diverging results illustrate the fact that, even if a mathematical model accurately predicts the diffusion of a determined tomato set, there is still the issue of heterogeneity among fruits. Processing conditions that would efficiently peel 1 tomato could be insufficient or excessive for a different fruit within the same lot.

### Quantifying peeling performance

Peelability quantification methods vary widely in the literature. Some authors, such as Schlinime and others (1984), make use of USDA’s grading guidelines for canned tomatoes. These guidelines deem incomplete peeling as a defect that decreases product quality. For example, “Grade A” tomatoes cannot have more than 2 square inches of peel per <2-lb container; “Grade C” tomatoes, on the other hand, have no established limit to the amount of leftover peel (Agricultural Marketing Service 2015).

A summary of grading scales found in the literature is included in this review. Only those scales specifically created to measure tomato peelability are shown. It should be noted that, in many cases, authors use more than 1 parameter to evaluate ease of peeling. Descriptors such as “% tomatoes with no peel,” “peeling losses,” and “yield” are often used in conjunction with (or instead of) peelability scales to describe the overall ease of peeling found in tomato batches and/or cultivars (Pandrangi and Barringer 2000; Garcia and others 2006; Zhang and others 2013).

Although objective quantification methods such as the “peel index” (skin remnants measured by placement over a standardized grid (Garcia and Barrett 2006a) are available, most peelability grading scales found in the literature are subjective and rely heavily on visual evaluations by scientists or technicians, and trained grading panels.

**Two-point scales.** Previous studies which included the use of 2-point scales for evaluating the peeling performance is summarized in Table 1. According to these studies, Das and Barringer (1999) used the descriptors as either peeled when more than 95% of the peel is removed or not peeled when less than 95% of the peel is removed. On the other hand, Barrett and others (2006) described a tomato peeled when less than 1 cm² was left on the surface.

**Three-point Three- and five-point scales.** Two studies which utilized 3-point scales for the assessment of the degree of tomato peelability are shown in Table 2. Juven and others (1969) used 3 descriptors (good, fair, and poor) to evaluate the ease of peel removal, while Hart and others (1974) used the descriptors of completely peeled, partially peeled, and unpeeled to describe how complete the peeling application is. Additionally, several authors utilized varying 5 descriptors to assess the peeling performance as summarized in Table 3 (except Yaniga (2007), who had only 4 descriptors).

**Ten-point scale.** Santos and others (2014) reported that when peelability is visually evaluated by a trained grading panel, it is possible to obtain very low standard deviation among the panelists’ assessments. After peeling a batch of tomatoes with lye, a panel composed of 3 members evaluated the percentage area left without skin on the surface of the fruits. The grading scale used went from 0 to 10 and continuously increased according to the percentage area peeled. A zero, for example, was given when no skin detachment was observed, a 7 when approximately 30% of the skin remained, and a 10 when 100% of the peel was removed by the peeling process. The standard deviation for the measurements was reported to be 0.2 on a scale from 0 to 10. Such grading method could offer a more convenient alternative to other methods such as the peel index which has been reported to be imprecise and difficult to execute (Garcia and Barrett 2006a).

**Additional considerations.** Thomas and others (1978) suggested that, in addition to assessing peeling performance and raw material losses, the overall economic efficiency of the peeling process is of-upmost importance. Factors such as energy costs and peeling times should be evaluated and translated into actual dollar costs per case. Moreover, Milczarek and McCarthy (2011) propose that tomato processors are concerned with the final state of the peeled fruits and not only with the degree of peeling. Therefore, they suggest “peeling outcome” (as opposed to “peelability”) as the metric of interest. In their 2011 publication, they attempted to predict peelability by using magnetic resonance (MR) data which is hypothesized to correlate with the characteristics in the fruits’ pericarps. The following possible outcomes were listed:

- Whole peeled (the only desirable outcome)
- Some skin
- Broken and some skin
- Broken
- Unpeeled
- Fell out at peeler
- Fell out at cord scrubber
- Fell out at pinch roller
- Other (identification tags were lost or retrieved from an inconclusive location)

Although the results of the study show some promise for the application of MR in the prediction of peelability, it is not clearly specified how the characteristics in the fruits’ pericarps (as measured by MR) would correlate with fruits falling out of the production line, or with identification tags being lost in the process.

### Fruit tagging procedures

An ideal fruit tagging method needs to balance simplicity, low cost, and reliability. With the recent use of technologies such as spectroscopy and MR that associate characteristics of a particular fruit (for example, chemical profile of its peel or state of the fruit’s pericarp) with its peeling outcome, scientists have the need to tag tomato fruits individually prior to the peeling process in a manner that ensures the tags will remain in place and be easily identifiable at the end. The following are 2 “individual-fruit tagging” methods found in the literature.

**Radio frequency ID (RFID) method.** The method reported by Milczarek and McCarthy (2011) is a practical option for researchers who have the budget to acquire radio frequency tagging equipment. The steps involved are:

1. Each fruit is individually tagged by injecting a numbered RFID chip (12-mm length × 2-mm diameter) through the stem scar, approximately 10 mm into the columella.
2. Fruits undergo the peeling process of choice.
3. The technician in charge of determining peeling outcome is able to identify the fruits by using a portable RFID reader.

**Low-cost method.** A more affordable alternative for individual fruit tagging was developed by Santos and others (2014). The supplies needed for this tagging method are not only low cost but
can easily be found in major grocery/home-improvement stores. The steps involved are:

(1) Tag manufacture: plastic sheet (“transparency film”) fragments of approximately 0.5 cm × 0.5 cm are labeled by hand with a permanent marker, covered with a clear silicon paste (such as LOCTITE clear silicon adhesive for extreme conditions, Henkel Corporations, Avon, Ohio, U.S.A.) and the silicon is allowed to dry.

(2) Fruit tagging: A small incision is made on the fruit stem scar with a thin, retracting blade cutter (approximately 0.6-cm wide). Tags are inserted through the opening and gently pushed in with dissecting forceps. Once the tags are inside, the opening is sealed with silicon.

(3) Fruits undergo the peeling process of choice.

(4) The trained panel in charge of determining peeling outcomes chooses a fruit, assigns a peelability score to it, and then immediately the fruit is opened by hand to retrieve the tag and to establish its identity.

It should be noted that both individual tagging methods found in the literature chose to insert tags through the stem scar, suggesting that this location is the most likely to maintain its integrity throughout the peeling process.

**Peeling aids**

A continuous desire to improve peeling yields has led processors to use various peeling aids, most often involving “dips” before the actual submersion in lye solution and/or the use of additives such as surfactants. Surfactants are substances known to reduce the surface tension of water, thus increasing the capillary forces in porous materials (Rahman 1999). They are applied during lye-peeling for the purpose of improving the contact between the cuticle and the lye solution (Das and Barringer 1999). Unlike some other areas in peelability research, the debate on peeling aids seems to have consensus: they are generally believed to help (Juven and others 1969), and a possible explanation has arisen that attributes the improvement mostly to the ability of peeling aids to eliminate cuticular waxes from the tomato surface (Das and Barringer 1999).

**Physiognomy**

Given that the scientific method is based on observation, it is only natural to find several peelability studies that focus on the most obvious attribute of tomato fruits: their physical appearance. The works of Diane M. Barrett and Elisabeth Garcia are prominent on this particular topic. In 2001, Barrett (2001) evaluated the following physical attributes of tomato fruits: color, density, height, weight, width, shoulder height, stem scar diameter, number of locules, gel state, seed number and weight, pericarp wall thickness, and red layer thickness. After steam-peeling the fruits, a mathematical model was constructed based on the correlation of measured physical attributes with observed levels of peelability. The model was designed with the purpose of performing future differentiation between tomatoes for paste and tomatoes for whole/diced tomato products. Width, stem scar diameter, pericarp thickness, and red layer thickness were chosen as predictors for the model by means of discriminant analysis. The model created had 90% allocation accuracy for the pilot-plant tests. The experiment’s report included a closing remark indicating that the developed model was being tested in an actual processing plant and that, despite problems with varietal factors, the results indicated some success.

In 2006, Garcia and Barrett (2006a) reported that cultivar was indeed a very important factor affecting the quality of processing tomatoes (in accordance with Schlimme and others 1984). No reference was made in regard to the 2001 study, but it can be inferred that the model designed that year did not meet the desired

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**Table 1—Two-point scales used for peelability quantification.**

<table>
<thead>
<tr>
<th>Peelability scale defined by...</th>
<th>Das and Barringer (1999)</th>
<th>Barrett and others (2006)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Descriptors used</td>
<td>“Peel left on the tomato surface”</td>
<td>“Peeled tomatoes”</td>
</tr>
<tr>
<td></td>
<td>Peeled (≤5% peel attached)</td>
<td>Peeled (peel completely removed or &lt; 1 cm³ left)</td>
</tr>
<tr>
<td></td>
<td>Not peeled (&gt;5% peel attached)</td>
<td>Unpeeled</td>
</tr>
</tbody>
</table>

**Table 2—Three-point scales used for peelability quantification**

<table>
<thead>
<tr>
<th>Peelability scale defined by...</th>
<th>Juven and others (1969)</th>
<th>Hart and others (1974)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Descriptors used</td>
<td>“Ease of removal of the peel”</td>
<td>“Completeness of peeling”</td>
</tr>
<tr>
<td></td>
<td>Good</td>
<td>Completely peeled (no skin remaining)</td>
</tr>
<tr>
<td></td>
<td>Fair</td>
<td>Partially peeled (50% or more of their skin removed)</td>
</tr>
<tr>
<td></td>
<td>Poor</td>
<td>Unpeeled (more than 50% of their skin remaining)</td>
</tr>
</tbody>
</table>
Table 3–Five-point scales used for peelability quantification.

<table>
<thead>
<tr>
<th>Peelability scale</th>
<th>Description</th>
<th>Visual/subjective grading system</th>
<th>Cuticular influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>5–1 Continuous scale higher to lower</td>
<td>Good peeling (&gt;75%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 (As class 3, but less than 50% of all peel is still attached, or small flags at the stem scar were considered peeled)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 (More than half of the peel is still attached, or small flags at the stem scar were considered peeled)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 (More than half of the peel is possible but with little effort)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 (Less than half of the peel was removed)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 (No outside removal)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Visual/subjective grading system is clearly specified.
- The cuticle is the first barrier against lye penetration during commercial peeling. Studies have been performed in order to understand how specific cuticular characteristics may affect the ease of peeling of tomato fruits. This section of the review describes some of the relevant work on the topic.
- Microstructural cuticular properties have been contemplated as potential indicators of peelability. Das and others (1995) studied

Tomato defects

After almost a decade studying peelability, Barrett’s research team recognized that a truly representative model for the prediction of tomatoes’ peeling needed to encompass the influence of tomato defects. Before this point, most trials had been deliberately carried out using only perfect fruits in order to rule out unnecessary variation.

The first study involving “imperfect” tomatoes (Barrett and others 2006) concluded that the presence of defects in general decreases the percentage of tomatoes peeled and the yield of whole peeled tomatoes. Some defects had a negative impact on peelability while others did not. Under-color, yellow eye, and sunburn were those that affected peelability the most (only 21% to 37% peeled tomatoes). The presence of zippers, gold flecks, stems attached to tomatoes, shallow flesh cracks, and skin cracks, on the other hand, had outcomes comparable to that of perfect fruits. In a subsequent study titled “Can we predict peeling performance of processing tomatoes?” (Garcia and others 2006), the authors took a broad look at the vast array of information they had collected over the years and attempted to develop acceptable models for predicting of peeling performance of processing tomatoes. Two models were developed using variables that had exhibited association with peelability in the past (weight, width, pericarp, red layer, number of days at temperature above 90 °F, and number of days with temperature above 100 °F), one modeled ideal batches of tomatoes and the other normal fruits. Several types of statistical analysis were performed on the models, each one pointing at different possible predictors for peeling performance. Although it is not clear which, if any, physical factors could be considered as definitive “universal” predictors of peeling performance, there is something interesting about the closing observations the authors provide. The conclusions highlight a variable that was not mentioned in their previous studies: the temperatures experienced during the fruits’ growing season. It is hypothesized that temperature may have an indirect influence on peelability by being associated with the occurrence of defects; however, it should be noted that the effect of temperature may also indicate the existence of environmental influences on the overall developmental process of the fruits. As a final word of advice, Barrett and Garcia warn that favorable results on a pilot-plant study titled “Can we predict peeling performance of processing tomatoes?” (Monti 1980). The conclusion remarks for the 2006 report stressed the influence of the growing season as the main contributor to the variation observed experimentally.

Cuticular influence

The cuticle is the first barrier against lye penetration during commercial peeling. Studies have been performed in order to understand how specific cuticular characteristics may affect the ease of peeling of tomato fruits. This section of the review describes some of the relevant work on the topic.

Microstructural cuticular properties have been contemplated as potential indicators of peelability. Das and others (1995) studied
the susceptibility of cells to damage during peeling and found an association between cell size and loss of integrity. It was concluded that, in general, the bigger the cells the less damage they showed after peeling. Interestingly, when tomatoes displaying the defect known as yellow shoulder were examined under the microscope, the defective areas had smaller cells than normal tissue; however, contrary to what would be expected, these abnormal areas did not collapse or lose their shape during lye treatment. Additionally, they did not peel. Since yellow shoulder areas have been found to have substantial greater content of calcium compared to normal tissue (Picha 1987), it is possible that there may be a major number of calcium–pectin complexes in the cuticle that are not affected by NaOH (Das and others 1995).

A study conducted by Mohr (2007), which used submersion in boiling water instead of lye, found that 2 anatomical features associated with easy peeling were an abrupt cell size gradient in the exocarp and the absence of small cells in the mesocarp. Supposedly, the steep change in size paired with a natural tendency towards wall separation favors skin detachment in this zone. A later study on the subject (Barringer and others 2008) concluded that, even when larger cells seem to be less damaged by lye peeling, there was no correlation between the microscopic cellular structure of a fruit and its peelability.

The microscopic structure of tomato peels is not the only factor that may influence peelability; cuticular composition can have an effect too. Floros and Chinnan (1989) measured the diffusion of sodium hydroxide through tomato’s peel and discovered that it was almost $10^4$ times slower than that in water. They ascribed this behavior to 1 of 3 possible causes: (1) the epicuticular waxy layer’s resistance to mass transfer, (2) a tightly packed cellular structure of the skin, or (3) the tissue’s acid content counteracting the alkalinity of sodium hydroxide.

Although other authors have also been concerned about the neutralization effect that tomato’s acidity can have on NaOH (Thomas and others 1976; Lorenzo 1983), there have been instances were tomatoes had significantly reduced acidity in comparison to the control, and yet were harder to peel (Pandrangi and Barringer 2000). The same is true for areas exhibiting yellow shoulder, which have higher pH and are still unaffected by NaOH (Das and others 1995). For these reasons, as long as the pH of the lye solution utilized throughout the day is maintained above the minimum levels required for peak rate of lye diffusion, the fruits’ inherent acidity would probably not be a major problem. With the issue of acidity resolved, the 2 remaining factors are dense cellular structure and wax resistance to mass transfer. As it will be seen next, these 2 factors are not necessarily exclusive.

The influence of waxes was demonstrated by a simple experiment where peeling performance was measured on tomatoes with and without their waxes. When dewaxed fruits were peeled, peelability significantly improved. The improvement was accentuated with increased peeling temperatures that are more efficient at dissolving the waxes. Percent of peeled tomatoes went from 16% at room temperature to 93% at 45 °C. Above this point, the detrimental effect of heat on tissue-softening impeded further improvement (Das and Barringer 1999). There are few discrepancies concerning the phase transition temperature of the wax fraction that works as the main barrier to lye diffusion. One study reports that wax liquefies at temperatures above 45 °C (Floros and Chinnan 1990), yet another study indicates it melts at and below 45 °C (Das and Barringer 1999). Considering that the ubiquitous variations among cultivars may have influenced the results, it would be safe to suggest the temperature for phase transition to be somewhere between 40 and 50 °C.

As it can be seen, there is strong evidence indicating that the presence of waxes does influence peelability; however, the permeability of the cuticle is not correlated with its thickness or wax coverage alone (Floros and Chinnan 1989; Schreiber and Riederer 1996; Leide and others 2007). The action of waxes seems to be more a result of its chemical/molecular structure or arrangement.

Santer and Chamel (1998) assessed the role of cuticular waxes for the transfer of polar and nonpolar molecules through plant cuticles. They concluded that it was the cutin polymer matrix and its relationship with waxes—not the waxes as such—the ones that constitute the main barrier to the diffusion of hydrophilic compounds. Rheological studies showed that waxes reduce cuticular elasticity and susceptibility to fracture (Petrasek and Bukovac 1995). The purported explanation is that, as polymer fillers (Meares 1965) and reducing the mobility of the cuticular matrix, they exert a “cross-linking effect” that increases rigidity of the flexible cutin matrix (Zlotnik-Mazor and Stark 1988). From a chemical point of view, the literature points at waxes’ content of $n$-alkanes and triterpenoids as the main determinants of the transpiration barrier. Studies with tomato mutants have indicated that a reduction in $n$-alkanes and an increase in triterpenoids is associated with increased water permeability (Vogg and others 2004; Leide and others 2007).

Other important components of the waxes are flavanones and chalcones that are mainly stored on tomato peels (Iijima and others 2008). It has been previously mentioned that flavanones, like naringenin chalcone, may reduce available hydroxyl groups in the cutin matrix and decrease volume within the cuticular network, thus affecting the rigidity of the membrane (Bargel and Neinhuys 1995; López-Casado and others 2007). Their side chains and cross-linking could also play a role in the irreversibility of the wall extension (Schopfer 1996). Altogether, it is believed that these compounds influence the water permeability through the cuticle (Luque and others 1995). Since the primary site for water-cuticle interaction is thought to be the free of hydroxyl groups on the peel’s matrix that can form hydrogen bonds with water (Petrasek and Bukovac 1995), and since the presence of flavanones and chalcones could reduce the availability of hydroxyl groups, 1 possibility is that flavanones and chalcones could hinder cuticle hydration and, therefore, decrease the susceptibility of the cuticle to fracture.

A study conducted by Saladí and others (2007) utilized tomato fruits with extreme delayed deterioration (DFD) and compared them with a cultivar of normal ripening (AC). Whereas the AC variety collapsed shortly after fully ripe, the DFD fruits remained almost intact for over 6 mo. Such remarkable shelf-life was attributed to the excellent support and barrier properties of the cuticle. Despite having lower levels of $n$-alkanes (previously associated with increased water permeability), the DFD fruits displayed minimal transpirational water loss. The fruits had a very particular trait; when the naringenin chalcone content of AC and DFD fruits was assessed, AC fruits exhibited the characteristic yellow orange color ascribed to naringenin chalcone, but, contrary to what would be expected, the DFD fruits did not present the chalcone (Saladí and others 2007).

**Maturity and developmental conditions**

From a physiological point of view, a fruit is mature when it is able to continue ontogeny, even if detached from the plant. Ripening, on the other hand, is the process that ensues later and results in characteristic changes in composition, color, texture, and
other sensory attributes that give the fruit its food quality (Kader 1999).

Maturity is considered a factor that affects tomato peelability, and harvest dates are often selected by estimating the time when 90% of the processing tomatoes in a field are red (Garcia and others 2006). Many efforts have been done to develop a reliable technique for the nondestructive determination of tomatoes’ internal maturity. The technologies used in this pursuit include Raman spectroscopy (Qin and others 2012), nuclear MR (Saltveit 1991), near-infrared technology (Sirisomboon and others 2012), and handheld visible-NIR spectrometry (Tiwari and others 2013). Still, determining maturity in tomatoes can pose a challenge, especially considering that fruits that have the same chronological age may have a very different age physiologically (Gustafson 1929).

Probably for this reason, there are many diverging reports on the effect that maturity can have on peelability. For the sake of simplicity, it will suffice to say that, although peeling losses can increase with later harvests, the completeness of peeling does not always follow the same trend (Yaniga 2007; Barringer and others 2008).

The addition of some chemicals as supplements while the fruit is still on the field has been studied. The level of nitrogen fertilizer is not related to peelability (Barringer and others 2008) and the application of foliar calcium is inversely related to it. It should be noted that the addition of calcium increased cuticle thickness (up to 15%) as well as the resistance to breakdown induced by lye (Pandrangi and Barringer 2000). The purported mechanism of action explaining the decrease in peelability is the strengthening of the pectin–pectin bonds on the cuticle by means of calcium-binding.

There is an indication that tomato plants are susceptible to environmental factors such as soil, temperature, light, and rainfall (Bolas and Melville 1933; Panthee and others 2012). When ambient conditions are not favorable, the plants are stressed and can respond in numerous ways to either a single source of stress or abiotic stress combinations (Rivero and others 2014). The developmental stage at which the stress occurs, as well as the frequency of the stress, may influence subsequent events. For example, when the tomato plant is first exposed to water stress in early stages, it is better able to recover after rewatering, even if a second stress is imposed. The same is not true if stress is imposed for the first time at later stages (Abou Hadid and others 1986).

In tomato fruits, water stress has been found to correlate with acidity (Monti 1980), with increased rate of ethylene biosynthesis (El-Beltagy and Hall 1974), and with higher total solids (Barbagallo and others 2013). Light stimulates the production of cuticular phenolics and flavonoids (Hunt and Baker 1980; Giuntini and others 2008); high temperatures (above 32 °C) inhibit the synthesis of lycopene (Hobson and Davies 1971; Monti 1980), and if the temperatures exceed 30 °C for long periods, yellowish discoloration and irregular ripening can also occur (Grierson and Kader 1986; Das and others 1995).

Hydrothermal conditions during fruit growth can also influence levels of magnesium and calcium, fruit weight, and number of locules, but do not seem to have a direct effect on pericarp thickness, fruit shape, reducing sugars, phosphorus, and L-ascorbic acid content (Skowera and others 2014).

In general, the growing season and growing conditions have been reported to be “apparently more significant than anything else, even the genetic background of the cultivars” (Garcia and Barrett 2006a) when it comes to tomato peelability. They can have an effect on anatomy and water conductance of the cuticles and may even influence epicuticular waxes’ composition and/or structure (Guichard and others 2005).

Leonardi and others (1999) performed a very interesting study to elucidate the effect of climate conditions on cuticular transpiration and on average total fruit conductance to water vapor. It was found that vapor pressure deficit (VPD) and air temperature during fruit development were tightly related to transpiration. Fruits grown under high VPD (drier conditions) developed thicker cuticles, had lower g and lower transpiration rates. Overall, the cuticle effect on g was attributed to irreversible changes taking place during fruit growth in response to atmospheric VPD levels. The growing season has also been correlated with the amount of NaOH necessary for successful peeling. Juven and others (1969) reported that Roma tomatoes that needed 18% NaOH to be peeled when harvested at the end of August only needed 8% when peeled 6 wk later, despite being grown on the same field.

Overall, it seems that the influence of environmental factors on phenotypic stability of tomato could have a real effect on peelability. Fortunately, this topic is increasingly gaining attention given its applications in breeding programs and general crop production (Huehn 1990).

Postharvest handling

There is a good number of studies in the literature dealing with the postharvest behavior of tomatoes destined for fresh consumption. Unfortunately, there is not a similar abundance of sources regarding the postharvest behavior of tomatoes for processing. An explanation could be the relatively immediate use of processing tomatoes which are in most cases taken directly from the field to the processing plants. However, transportation conditions could have an effect on the transpiration barrier of the fruits, even after short periods of time.

A short-term, reversible response in fruit transpiration has been reported to be associated with instantaneous changes in cuticular hydration due to vapor pressure difference in the environment (Leonardi and others 1999). In this regard, vapor loss has been suspected to originate a change in the peel’s structure by means of rearrangement of the wax platelets. Transpiration can show a progressive reduction as soon as 3 h after plant detaching. Linke and Geyer (2002) utilized a novel technique to measure the transpiration behavior of tomatoes under simulated postharvest conditions. It should be noted that the fruits in this case were orange–red in coloration and the handling procedures emulated during the study were those typical for tomatoes destined to fresh consumption; nevertheless, important observations arise from the study. The main point that can be drawn from Linke’s work is that tomatoes are able to compensate initial higher rates of water loss during the postharvest period by exhibiting subsequent higher transpiration barriers. Tomatoes were transported inside containers with different permeabilities, under a variety of climatic conditions. The effect of the handling procedures on transpiration and quality properties of the tomatoes was evaluated. Containers with higher air permeability allowed for higher water loss of the fruits. Remarkably, the fruits in these containers experienced an increase in transpiration and respiration resistance to the point where, at the end of the postharvest simulation, fruits in all the packaging units had almost identical total water loss.

In one study, water loss was concomitant to a visible loss of gloss, which could be explained by the spontaneous wax exudation previously reported by Charles and others (2008) on senescent tomato fruits after storage, and that is associated with a decreased movement of hydrophilic molecules (Wilson and Sterling 1976).
There is a possibility that this increase in cuticular wax could be a defense mechanism exerted by the fruits against dehydration, akin to tobacco leaves which are able to increase wax load repeatedly after periods of drought, and do not lose that ability even with advanced age (Cameron and others 2006). More research is needed in this area in order to establish the rates of wax exudation, the effect of transportation conditions on it, and to determine if this purported wax production has any relevance to peelability. The developmental stage of the fruits also had an effect on the transpiration barriers, with tissue resistance decreasing after a defined stage of ripeness. However, the influence of the climatic conditions was predominant. The study showed that the changes in the barrier properties of the fruit eventually lead to improved quality and lower microbial activity. It must be stressed that the measurements reported by Linke and Geyer (2002) did not always yield statistically significant differences and, even if they had, the implications on peelability are still unknown. Another relevant work regarding postharvest behavior of processing tomatoes was included in the work conducted by Yaniga (2007), who found that, as tomato fruits age on the vine, changes take place that lead to harder peeling; but the speed at which these changes occur is so slow that they do not represent a problem for processors (mature red tomatoes would need to remain more than 1 mo on the vine for problems to arise). Conversely, once tomatoes are detached from the vine, they become significantly more difficult to peel as soon as 3 d after being picked. It would seem that those changes that decrease peelability over time are accelerated once the fruit is harvested.

**Novel Methods for Peelability Prediction**

**Magnetic resonance**

In 2011, Milczarek and McCarthy (2011) proposed the use of magnetic resonance imaging (MRI) paired with multivariate image analysis (MIA) to predict peeling outcomes. They hypothesized that peelability was determined by internal features in tomatoes, particularly by the state of the pericarp. Since MRI is able to characterize the environments of protons inside plant tissues (Hills and Clark 2003), the scientists believed it could also be used to evaluate internal characteristics of the fruits. Processing tomatoes were obtained from an industrial plant, individually tagged, and inserted into a 7-tesla MRI system (Bruker Biospin MRI, Inc., Billerica, Mass., U.S.A.) for data collection. Twenty-eight MR images were collected from the middle section, or middle “slice” of each tomato sample. After imaging, fruits were sent through a pilot-plant peeling line, their peelability was graded and finally assigned into 1 of 9 possible peeling outcomes. MRI is able to collect the tridimensional data from the tomato samples and represent it in a 2-dimensional manner. MIA then correlates the resulting MRI pulse sequences with any metric of interest, in this case with the peeling outcomes. Two different MIA models were created, one based on partial least squares discriminate analysis (PLS-DA) and another on soft independent modeling of class analogy (SIMCA). The best performing model was the one developed with PLS-DA, which correctly classified 81% of the fruits in the “whole peeled” category, and indicated that MR images were yielding information associated with peeling outcomes.

In 2013, Zhang and others (2013) did an additional study involving MRI. This time, their objective was to explain the previously established correlation between MR images and tomato peelability. The scientists focused on characterizing the red layer and exploring how it correlated with both ease of peeling and signal intensity of the MR images. Samples of 3 processing tomato cultivars were obtained. Some fruits were cut in half to measure the thickness of their red layers, other fruits were imaged on a 1T permanent magnet MRI system (Aspect AI, Industrial Area Hevel Modi’in, Shoham, Israel). After the peeling process, the peelability of each cultivar was expressed as the percentage of tomatoes with no peel or with peel only attached to the stem area. Although the red layer and pericarp features depicted in MR images did show correlation with peelability, the differentiation among levels was only moderate and further research was needed to establish definitive quantitative relationships between MRI data and ease of peeling.

**Handheld infrared spectroscopy**

In 2014, Santos and others (2014) examined the feasibility of using handheld infrared spectrometers to predict peelability. Infrared sensors not only show good potential to estimate quality parameters in tomato products (Wilkerson and others 2013), they also present many advantages such as relative rapidity, low cost, high throughput (Downey 1998; Smith 1998), and the convenience of easily taking battery-operated units to processing plants and growing fields. Since this technology is sensitive to the presence of functional groups in the samples, the hypothesis was that it could detect cuticular characteristics possibly associated with ease of peeling. A total of 122 tomatoes from different processing varieties were obtained and individually tagged. Their spectra were then collected with a TruDefenderTM FT infrared handheld spectrometer (Thermo Scientific, Inc., Wilmington, Mass., U.S.A.) equipped with a single-bounce diamond-attenuated total reflectance (ATR) crystal. After undergoing dye-peeling, a grading panel visually scored the peelability of each fruit and the grades were then correlated with infrared spectra by means of partial least square regression (PLSR). The residuals in the regression had non-homogeneous variance and the model was most effective at predicting tomatoes that would be “very hard to peel.” The most important elements used for the prediction were the infrared frequencies associated with bound phenolics and proteins in the cuticle.

**Conclusion**

The literature regarding tomato peelability has been contradictory in many cases. Several areas have been subject to ample debate for many years. Divergent conclusions are probably not due to faulty investigations, but rather to the extreme variability found among cultivars, the effect of growing seasons, and maybe even the effect of climatic conditions the day of harvest or during transportation to the processing plants. The substantial amount of research that has been carried out concerning the ease of peeling on tomato fruits can only be explained by a real need from the industry for a reliable, practical solution for this problem. There may be a day when breeders, through gene manipulation, are able to develop a perfect cultivar, one that allows for on-vine storage for prolonged periods of time, one able to undergo mechanized harvest and transportation with minimum damage, and one that additionally peels homogeneously and with ease. Some work has already been done in that aspect, but until that day arrives, efforts can be directed at providing processors with scientifically sound guidance for peelability assessment of their incoming loads.

**Author Contributions**

Huseyin Ayvaz searched for the prior studies, formatted the manuscript. Alejandra M. Santos searched for the prior studies and built the main form of the manuscript. Luis E. Rodriguez-Saona created the idea and guided the work.
Understanding tomato peelability...


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