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An overview of recent studies of tomato (*Solanum lycopersicum* spp) from a social, biochemical and genetic perspective on quality parameters

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Keywords: Tomato, postharvest management, quality traits

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Abstract

Tomato is the second most important horticultural product cultivated worldwide. For research, tomato is considered a model organism of the Solanaceae family, and has therefore been, and is still a major crop subject of studies both in the laboratory and under field conditions.

This introductory paper aims to explore origin and distribution, economic importance, social impact, and postharvest losses of tomatoes from field to consumption.

The present literature overview summarizes variation in quality traits such as bioactive compounds in fruit, as well as in sensory factors, e.g. color, shape, texture and volatile compounds. From the health perspective, regular intake of tomato fruit consumed fresh, as a juice, or canned, increase levels of carotenoids, lycopene, vitamin C, and polyphenols compounds in the daily diet, which are reported to be beneficial to health and lower the risk of some diseases, such as some forms of cancer and diabetes. Regarding quality traits, internal traits as well as color, size, and texture, are determined by the presence or absence of various compounds in the tomato, while resistance to mechanical damage is influencing external quality traits.

Quality traits are affected by environmental conditions during pre- and post-harvest stages. Tomato production management influences the yield, acceptability, price and length of shelf life but differently in each tomato cultivar.

Finally, this introductory paper presents a brief overview of studies concerning genetic diversity among domesticated and wild relatives and their impact on quality traits, including recent studies of tomato biodiversity, genetic identity of cultivars and their wild relatives. In addition, a few studies are mentioned concerning trans-formed plants, showing the importance of different enzyme activities in relation to effects on internal and external quality traits

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1 General perspective of tomato crop and its societal importance

1.1 Origin and distribution of tomato

The center of origin of tomatoes have been debated by many, some are suggesting the center to be the dry coastal desert of Peru (Jenkins, 1948, Preedy and Watson, 2008, Blanca et al., 2012), while others have suggested a dual center with one part in the coastal region between the Andes (Blanca et al., 2012) and the ocean and the second part from South Mexico to Guatemala (Bauchet and Mathilde, 2012). Wild relatives of tomato are distributed in the Andes from Ecuador, through Peru and to Chile (Peralta et al., 2005), growing between sea level and 3300 meters above sea level (Blanca et al., 2012) in diverse climatic conditions. The domestication is still unclear but linguistic evidence has postulated Peru and Mexico as the major regions of domestication (Peralta et al., 2006). Tomatoes are known to be used in cooking in Mexico by the Aztecs already 500 BC and were transferred to the rest of the world by the conquistadors after the capture of the Aztecs territory (Bergougnoux, 2014).

Taxonomically, tomato belongs to the Solanaceae family. The cultivated tomato belongs to the species *Solanum lycopersicum*, while *Solanum pimpinellifolium* is the closest wild relative with a divergence of only 0.6% nucleotide base pairs (The Tomato Genome et al., 2012). A range of other wild tomato relatives are available, e.g. *Solanum chmiewelskii, Solanum neorickii, Solanum chilense, Solanum habrochaites, Solanum pennilli, Solanum juglandifolium, Solanum ochranthum, Solanum lycopersicoides, Solanum sitiens, Solanume corneliomuelleri, Solanum arranum* and *Solanum galapagense* (Peralta et al., 2006). Despite the fact that wild tomato relatives have contributed limitedly with desirable phenotypic traits to current cultivated tomatoes, interesting alleles for future tomato breeding may still be available in uninvestigated tomato collections (Rendón-Anaya and Herrera-Estrella, 2017).

A large variation has been ascribed to the tomatoes as related to differences in shape, color, flavor and other parameters. Wild tomato are generally small as compared with the domesticated ones (Bergougnoux, 2014), and the differences in size is regarded as a result of changes in a total of six quantitative traits loci (QTL) during the domestication process (Bai and Lindhout, 2007, Bergougnoux, 2014).

1.2 Nutritional importance of the crop

Tomatoes are currently an important food component globally. The tomatoes are in fact the second largest vegetable both in terms of production and consumption (FAO, 2016). Reports from the United States show tomato as the second most consumed fresh vegetable with 6 kg/person in 2017 (USDA, 2016). Tomatoes are known as a source of vitamins and pro-vitamins (vitamin C, pro-vitamin A, β carotene, folate), minerals such as potassium, and secondary metabolites such as lycopene, flavonoids, phytosterols and polyphenols (Beecher, 1998, Luthria et al., 2006). Thus, 100 g of fresh tomato provides over 46%, 8% and 3.4% of the daily requirements of vitamin A (being 900 UE), vitamin C (being 82.5 mg) and potassium (being 3500 mg), respectively (Gebhardt and Thomas, 2002, Canene-Adams et al., 2005). Furthermore, processed tomato such as soup, paste, concentrate, juice and ketchup (Bergougnoux, 2014) also contribute positively to human health by the content of the mentioned compounds in these products.

1.3 Economic and social importance of the crop

Tomato is produced in temperate, subtropical and tropical areas around the world (Blanca et al., 2012) and it is the second horticultural crop produced in terms of yield in the world (FAO, 2016). Numbers from 2016 showed United States, China, India and Turkey as the countries with the largest production area (FAO, 2016, USDA, 2016). Fresh tomato production reached 163.719.357 tons in the world in 2013, and around 4.5% of the produced tomatoes are traded. The same year, the relatively highest tomatoes export was reported from Mexico followed by The Netherlands and Jordan, exporting 20%, 13% and 8% of their produced tomatoes, respectively. The revenue for the tomato export from these countries during the same year was 1195, 1675 and 517 US dollar/ton. Countries with the highest relative tomato import were during the same time Russia, followed by Germany and France with 12%, 10.3% and 7.8% respectively (FAOSTAT, 2013). Tomatoes are produced on field, but also under controlled conditions during autumn and winter. They are also produced in colder climates such as in the Scandinavian countries. Controlled conditions certify tomatoes production by the use of artificial lighting, increased temperature using heaters, as well as fertigation to produce high quality tomatoes (Oda and Saito, 2006).

Tomato production is expensive (USDA, 2016). The investments start by the use of certified seeds (Tüzel and Öztekin, 2017). Breeding and seed production are carried out in order to sustain the desires from growers, including desirable traits such as high yield and disease resistance, but also based on the destination of the cultivation and on consumer preferences (Carbonell et al., 2018, Yamamoto et al., 2016).

During production, recent technologies are used to maximize yield and product quality, and to reduce use of pesticides. Use of seedbeds, mulch, branch conduction, pruning, drip irrigation, and application of specific macro and micro nutrients during each development phase of tomatoes all contribute towards reaching the potential yield provided by the certified seeds (Tüzel and Öztekin, 2017). In open field production, mechanical harvest is used for fruits destined to industrial purposes and hand-picked harvesting for fruits destined to fresh consumption (USDA, 2016).

Fresh tomato prices have been found to suffer more from price variation than processed tomatoes, and the price is clearly dependent on the shipping-point price. It has been estimated that one-fourth of the final price is paid by the shipment chain (USDA, 2016).

1.4 Losses from the field to consumers

Food losses, happening from the field to consumers, are greatly affected by the locality where the product was grown, yearly climate conditions, season of cultivation and, nowadays, also on climate change (Kader, 2005, Hodges, 2010). Losses differ also depending on whether the production occurs in a Developed Country (DC) or a Less Developed Country (LDC). In DCs, the main losses (23%) are concentrated to the treatment of the product by the consumers (Kader, 2005). The largest losses in LDCs (up to 50%) are concentrated to the treatment of the product by the producers (Hodges, 2010). Thus, the losses start in the field (FAO, 1989) and have various causes, including biological spoilage (Hodges, 2010), awaiting for shipment (Campbell et al., 1986, Ayandiji and Omidiji, 2011), unavailability of storage facilities (Ayandiji and Omidiji, 2011), and injuries (Campbell et al., 1986).

In general, causes of losses can be divided into two groups: primary causes and secondary causes. Primary causes of losses include biological, microbiological, chemical, biochemical, mechanical, physical, physiological and psychological causes of loss (FAO, 1981). For tomato fruits, two classes of injuries have been described: Injuries during the production, and mechanical injuries at harvest. A source of tomato losses is related to the over-ripening of the tomatoes on the plant (Campbell et al., 1986). Secondary causes of loss include unsuitable harvesting techniques, inappropriate containers for transport, unsuitable storage facilities, inappropriate transportation, unsuitable refrigeration, inappropriate drying equipment, traditional processing, legal standards, and lack of knowledge on management and bumper crops (FAO, 1981). Improper temperature management during harvest and storage will quickly result in a reduction in value of tomatoes (Hodges, 2010, Ayandiji and Omidiji, 2011). During the entire value chain, losses occur also at harvest time, preparation during extraction of the edible part, preservation, processing, storage and transportation (Amalendu et al., 2003). Transport procedures may lead to postharvest losses through damages or injuries on the skin of the tomatoes, resulting in attacks of pathogens during storage (Campbell et al., 1986, Ayandiji and Omidiji, 2011).

1.5 Globalization and its impact on horticultural farmers. A social point of view

With increased globalization, horticultural products for exportation have become an alternative, providing job opportunities for small-hold farmers while this type of operation is rather labor intensive. For example, the export of horticultural products from the North of Mexico is absorbing workers from surrounding poor regions causing migration from the South of Mexico (Zabin and Hughes, 1995). Horticultural production systems are normally more work intensive than agricultural ones for obtaining the final product, as has been concluded from studies in Vietnam, Philippines and Bangladesh (Weinberger and Lumpkin, 2007). Thus, export of horticultural products is reducing poverty, by the provision of new and alternative jobs to small-scale farmers. (Weinberger and Lumpkin, 2007, Van den Broeck and Maertens, 2017). However, the farmer plays an important role by having impact on the quality of the produced tomato. The production is highly affected by the degree of the farmers' knowledge and on the support by regional and national institutions.

Lack of knowledge and support are known to increase harvest losses (Emana et al., 2017). Regional efforts to increase tomato production by smallholders in Africa has shown positive results, e.g. when novel leaf curl disease resistant tomatoes seeds were released in West Africa (Perez et al., 2017). In addition, regional efforts in the horticultural production chain is known to benefit women, due to the fact that women represent 80% of the work-force in this production chain, and increasing yield and quality of the produce results in more decision power for women within their communities (Alter, 2009).

2 Factors determining the quality of tomato fruits

Factors that influence product quality can be divided in two groups: Intrinsic factors (color, shape, and freedom of defects) and internal attributes such as texture, sweetness, acidity, aroma, flavor, shelf life and nutritional value (Hewett, 2006). Growers are mainly basing their decisions, as regards which cultivars to produce, on intrinsic factors desired by the buyer (FAO, 1989).
Crop management together with external conditions during the pre-harvest period will determine the quality of the product (FAO, 1989, Hewett, 2006), and during the best circumstances, this quality may be kept during the post-harvest period when quality improvements are not possible (FAO, 1989).
Opportunities to extend the shelf life of perishable commodities have been evaluated worldwide (Hodges, 2010), although adaptation to technologies prolonging shelf life is greatly dependent on knowledge of the grower (Kader, 2005).

2.1 Nutritional factors

2.1.1 Carotenoids, including lycopene

Carotenoids are well known as natural compounds involved in reducing the risk of development of several types of diseases such as diabetes, gastrointestinal and cardiovascular diseases e.g. by reducing the amount of oxidized low density lipoproteins (Hyman et al., 2004, Rao and Rao, 2007, Preedy and Watson, 2008). Carotenoids are also known to prevent development of degenerative diseases such as blindness, xerophthalmia and degeneration of muscles (Paliyath et al., 2008). In addition, carotenoids have been correlated to anticancer properties of stomach, lung and prostate cancer (Giovannucci, 1999, Wang et al., 2016). A recent study have shown that high-risk prostate cancer patients, constantly consuming lycopene through intake of a tomato sauce during a period of 4 years, significantly reduced their risk to contract prostate cancer. These patients also became low-risk prostate cancer patients after the 4 years period of lycopene consumption (Wang et al., 2016).

The health benefits of carotenoids have been attributed to their function as natural antioxidants. Lycopene is the major antioxidant carotenoid in tomato followed by β carotenoid (Hyman et al., 2004). Furthermore, α-carotene, β-carotene and β-cryptoxanthin are precursors of vitamin A, which is not the case for all carotenoids (Institute of Medicine, 2000, Apel and Bock, 2009).

Bioavailability of the carotenoids is highly important as related to their impact for human nutrition. Homogenization and heat treatments are common steps in transforming fresh tomato to other food commodities. Homogenization is normally breaking down the aggregated structures of the cell by changing the fiber network. However, homogenization at 90ºC in 30 minutes was shown to not change the fiber network (Colle et al., 2010). Similarly, another study demonstrated that homogenization at 100 MPa reduced bioavailability of carotenoids with one third as compared to that of not treated samples (Panozzo et al., 2013).Thus, homogenization is normally resulting in a higher stability of the fiber network, thereby leading to significantly lower bioavailability of carotenoids (Colle et al., 2010).

Other food processing steps, such as cooking, are instead known to contribute to breakdown of the cell walls, thereby facilitating bioavailability of carotenoids (Shi and Le Maguer, 2000). In addition, bioavailability of carotenoids increases with the presence of lipids, as carotenoids are fat-soluble pigments (Rao and Rao, 2007). Carotenoids combined with lipids are known to result in an isomerization of the lycopene. Therefore, through isomerization with corn oil, the bioavailability of lycopene from processed tomato combined with corn oil was found to be 3-4 times higher as compared to that from fresh tomatoes combined with corn oil (Gartner et al., 1997, Shi and Le Maguer, 2000).

The most accurate method for objective detection and quantification of carotenoids is to use HPLC (Serino et al., 2009). Thus, accurate detection of lycopene in fresh, canned or juice samples has been performed applying HPLC methods (Davis et al., 2003, Hyman et al., 2004). However, spectrophotometric and colorimetric methods are also commonly used to quantify lycopene. Choice of method and accuracy of results are highly dependent on qualified labor, time and accuracy needed (Davis et al., 2003, Hyman et al., 2004).

2.1.2 Vitamin C including ascorbic acid

Tomato is an important source for humans of vitamin C, including ascorbic acid and some, generally low, amounts of dehydroascorbic acid. No significant differences was found in quantity of ascorbic acid for different types of tomatoes, e.g. salad tomato versus those for processing. However, ascorbic acid was among the components in tomato highly sensitive to thermal degradation (Abushita et al., 2000). Red tomatoes contain approximately 19 mg of vitamin C (Nunes, 2008) and depending of the cultivar and growing conditions ascorbic acid contents is around 14.6 mg per 100 g of fresh red tomato (Abushita et al., 2000).

Synthesis and accumulation of ascorbic acid have been correlated with the maturity stage of tomatoes. Ripening tomatoes under storage conditions was shown to decrease the content of ascorbic acid in the tomatoes with up to 50% as compared to vine ripe tomatoes, demonstrating that accumulation of ascorbic acid is favored if the fruit reaches the maturity stage on the plant (Nunes, 2008). Salt stress during growth of tomato enhances the concentration of sugars, organic acids and amino acids, all characters being well appreciated by consumers (Passam et al., 2007).

The vitamin C content in fresh tomatoes could be preserved under storage conditions if modified atmosphere conditions was applied with a polyolefin films as an enclosure barrier with enough O_2 permeability to avoid anaerobic respiration (Passam et al., 2007). Exclusion of such barriers between the tomatoes and the atmosphere lead to the disappearance of vitamin C within 3 days (FAO, 1989). Also, vitamin C disappeared under heat conditions (FAO, 1989).

2.1.3 Polyphenols contents and antioxidant properties

Polyphenols are bioactive natural compounds present in vegetables, fruits and seeds (Quideau, 2011). A bioactive compound could be essential or non-essential for humans, but is mostly considered beneficial for the human health (Biesalski et al., 2009). Polyphenols can also be seen as “secondary metabolites” which presence are correlated to corresponding genes, although the content is also being influenced by the environment (Siracusa et al., 2012).

Polyphenol compounds are characterized by their phenolic structure in natural products (Tsao, 2010) and various types are soluble or insoluble in water (Papadopoulou and Frazier, 2004). The most common polyphenols in tomatoes are flavonoids, hydroxycinnamic acids and anthocyanins (Siracusa et al., 2012, Verhoeyen et al., 2002, Bovy et al., 2002), and the polyphenols are predominantly present in the tomato peel. In tomatoes, 30 different phenolic compounds have been determined being present; coffeic acid, caffeic acid-o-hexoside, chlorogenic acid, coumaroylquinic acid, coumeric acid-o- hexoside, cryptocholorogeic acid, dicaffeoylquinic acid, eriodictyol-o-hexoside, ferulic acid, ferulic acid -o-hexoside, feruoylquinic acid -o -hexoside, gallic acid, homovanillic acid, kaempferol-o-rutinoside-hexoside, kaempferol-3-o-glucoside, kaempferol-3-o-rutinoside, naringenin, naringen-in-o-dihexoside, naringenin-o-hexoside, neochlorogenic acid, o-acetylprunin, phloretin-c-diglycoside, phloridzin-c-diglycoside, protocate-chuic acid, prunin (naringenin-7-o-glucoside), quercetin, rutin-o-hexoside-pentoside, rutin-o-hexoside, rutin-o-pentoside, rutin (quercetin 3-o-rhamnosyl-glucoside) (Vallverdú-Queralt et al., 2010).

The physiological role of flavonoids is related to plant growth, protection from UV radiation due to pigment production, seed coat development, pollen growth and development of pathogen resistance (Harbone, 1995). Polyphenols’ role in protecting the plant from the attack of viruses and other microorganism has also been reported (Hemingway and Laks, 1992).

Pholyphenol compounds are suggested to influence human health; daily consumption of food containing polyphenols is suggested to reduce the risk of cardiovascular diseases (Bovy et al., 2002) by inhibition of the activity of kinase proteins, and arachidonic acid metabolism (Vassallo, 2008). Such diet may also prevent against chronic degenerative diseases (Vallverdú-Queralt et al., 2010), arthrosclerosis and free radical damage (Stewart et al., 2000). It has been reported that in human cells polyphenols may inhibit infections by herpes, pox, rabies and other viruses (Hemingway and Laks, 1992).

Table 1 shows a list of the most abundant phenolic compounds, reported in fresh tomato and in tomato sauce with or without olive oil. Bioavailability of naringenin and quercetin when digesting the tomatoes, was found to increase after mechanical intervention, heating or due to the addition of olive oil to the tomato sauce (Martínez-Huélamo et al., 2016).

Table 1. Levels of phenolic compounds in fresh tomato and tomato sauce with or without olive oil (Martínez-Huélamo et al., 2016).

Compound	Fresh tomato FW (mg/g)	Tomato sauce with oil (mg/g)	Tomato sauce without oil (mg/g)
5-CQA	0.0011	0.0008	0.0009
4-Caffeolyquinic acid	0.0011	0.0007	0.0006
CA hexoside I	0.0016	0.0014	0.0013
FA hexoside	0.0031	0.0025	0.0031
Homovanillic hexoside	0.0935	0.1278	0.1383
Niringenin	0.0048	0.0075	0.0066
Quercetin	0.0003	0.0003	0.0003
Rutin	0.0022	0,0054	0.0051

*Sample dose of 500 grams in fresh tomato and 250 grams in sauce; results presented in miligram per gram (mg/g); FW, Fresh weight; 5-CQA, 5-caffeoylquinic acid; CA, Caffeic acid; FA, Ferulic acid.

2.2 Sensory factors

2.2.1 Textural properties

Textural properties in food are defined as a group of physical properties that consumers can identify and evaluate during mastication (Bourne, 2014). In tomatoes, texture is generally changing during fruit ripening (Chaıb et al., 2007). A variety of methods exists, suitable for measurements of texture, and the most common ones are defined as rheological, sensory and morphological. The most commonly used rheological method study the flow of matter using an device called penetrometer. This method has been used to measure resistance to deformation in tomato. Significant differences of resistance among cultivars and their offspring have been reported (Chaıb et al., 2007).

Sensory methods are using trained panels, normally expressing textural properties by the use of terms such as fresh, firmness, mealiness, juiciness and skin toughness. How important the texture is for the quality traits can be divided into three categories: Critical if the texture determines the price of the commodity; important if the influence of the texture is significant but not a determinant of the price, and minor when texture is in principal not considered important at all. For vegetables, the texture is normally classified as important (Bourne, 2014).

Morphological studies have been carried out using microscopy to evaluate textural properties in tomato studying cellular structure of the pericarp (Chaıb et al., 2007).

2.2.2 Aroma and flavor

Generally, the flavor is a combination of the perception from retronasal aroma, and the perception from somatic fibers at the level of the trigeminal nerves and taste, meaning a combination of volatile and non-volatile compounds (Preedy and Watson, 2008). Flavor-influencing compounds include sugars (mainly sucrose, fructose, glucose); acids (mainly citric acid and malic acid) and about 400 volatile compounds. Vine ripe tomatoes have the highest level of those parameters (Preedy and Watson, 2008).

Several substances determine the final flavor of tomatoes. A key source is sugar. Changes in sugar content lead to dramatic changes in flavor, sweetness and sourness. The perception of sweetness can also be altered by reduction or the total absence of citric and malic acid (Preedy and Watson, 2008). Tomato carotenoids influence aroma and flavor. The composition of carotenoids is impacting the expression of aroma volatiles and flavor, while carotenoids in the fruit are degraded. Lycopene increase lemon-scented monoterpene aldehyde (Lewinsohn et al., 2005).

Postharvest storage of tomatoes under nitrogen was shown to reduce the amount of C6 volatile compounds in the stored tomatoes, as did storage of the tomatoes at low temperature. Returning the tomatoes to normal conditions, did not result in a full recovery of the content of volatile compounds (Boukobza and Taylor, 2002).

2.2.3 Total soluble solids and titratable acidity

Total soluble solids (TSS) is mainly composed of a blend of sucrose, hexose, citrate and malate that all together reach 78% of the total content. The remaining 22% represents minor solids such as minerals, phenols, soluble pectins, amino acids and ascorbic acid (Beckles, 2012). To evaluate this parameter it is necessary to use a refractometer, which is used worldwide due to its accessibility and adequate precision for commercial purposes (Malundo et al., 1995).

Acidity corresponds to the amount of acids in a solution. Titratable acidity (TA) is a type of measurement that deals with total acid concentration in any food. The core unit of acidity is hydrogen ions (H+) (Nielsen, 2017). In fruits juice titration is done with an alkaline solution until reaching a pH of 8.1(Wills et al., 1990).

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TSS is generally low in tomato, i.e. less than 5% for green tomatoes. When the tomato turns red, TSS increases to around 7%. Contrarily, acidity in tomato is high (0.9 g/100 g fresh tomato) at the green stage, but decrease to 0.4 g/100 g fresh tomato or less for red tomatoes (Serrano et al., 2005). The TSS:TA ratio can be used to predict the sensory taste perception of tomato (Beckles, 2012).

TSS and TA are thus important quality factors to include in breeding programs of tomatoes, although their measurements need to be carefully evaluated to correspond to consumers' desires and to not be biased by the design of the sensory tests (Mattheis and Fellman, 1999). Furthermore, a high TSS content in tomato is often associated with reduced yields (Stevens and Allen Rick, 1986), and with low quality appearance of the tomatoes under field conditions. The TSS values were also found to decrease under excessive irrigation (Lahoz et al., 2016) which might be related to the negative correlation between tomato size and TTS content, also being present between tomato size and sweetness (Beckles, 2012).

2.2.4 Enzyme activity

The main enzymes in tomato being involved in break-down of pectins; (i.e. pectolytic enzymes or pectinases), are polygalacturonase, pectin methylesterase (PME) and beta galactosidase (Van Dijk et al., 2006). Polygalacturonase is hydrolyzing the alpha 1,4 glycosidic bonds of the galacturonic acids during the ripening process of tomatoes (Fischer and Bennett, 1991). Thus, the polygalacturonase activity was previously thought of being the solely responsible factor of the softening of tomatoes during ripening due to degradation of the pectin although studies on transgenic tomatoes have shown this not being the case (Brummell and Harpster, 2001). The PME activity was shown to influence the pectin metabolism and was correlated to the content of total soluble solid contents in tomato (Tieman et al., 1992). A decay of PME activity was seen, exponentially over time, although low activity in transgenic tomatoes resulted in loss of tissue integrity with no change in fruit firmness (Tieman and Handa, 1994, Van Dijk et al., 2006).

2.2.5 Volatile organic compounds

Fruits normally contain a large amount of different volatile compounds that are responsible for the aroma and flavor of the fruit. Thus, a large amount of the different volatiles are synthesized during the ripening phase of the fruit and the content and composition of the volatiles are known to change with maturity stages of the fruit (Baldassarre et al., 2015). Volatile compounds are known to be part of the defense mechanisms against herbivores in tomatoes. Furthermore, damages by insects or by mechanical wounding produced changes in the composition and content of volatile organic compounds. (Raghava et al., 2010). Also, plants under attack of insects have been found to show higher concentration of volatile compounds compared with controls (Lara et al., 2015). Thus, a tomato plants attacked by *Tuta absoluta* expelled an increased amount of volatile compounds (76% to 86%), e.g. β-caryophyllene, α-pinene and α-phellandrene, and these compounds were found to attract *Macrolophus pygmaeus*, a natural enemy of the attacking insects (Lara et al., 2015).

Presence, amount and composition of volatiles compounds in tomato are affected by growing conditions. Low irrigation levels were found to be positively correlated with quality of tomatoes, with an increase in soluble solids and volatile compounds, resulting in improved aroma and lycopene content. However, the low irrigation levels also reduced the yield of production with 16.4% compared to the control (Lahoz et al., 2016). A treatment with HIPEF (high-intensity-pulsed electric field) on the tomatoes was found to preserve flavor quality and stability of the fruits (Aguilo-Aguayo et al., 2010). Furthermore, a treatment with the biocontrol agent, *Bacillus amylo-liquefaciens* strain T5, on tomato plants reduced the attack of *Ralstonia solanacearum* with approximately 85%. This biocontrol treatment promoted the production of 13 different volatile compounds when the plant was under attack and among these 10% had antibacterial activity (Raza et al., 2016).

When the tomato is ripe, the role of volatile compounds changes, from a protection role towards a role of attraction towards insects and other animals that can contribute with the dispersal of the tomatoes seeds. The main changes that occur in tomato are in terpenoids, aldehydes, ketones, carotenoids and lipids (Nath et al., 2014 , Baldassarre et al., 2015).

The starting molecules for biosynthesis of volatiles in tomato are proteins, carbohydrates and lipids. When the starting molecule is a protein, the resulting volatiles are aldehydes, alcohols, aromatic amino acids, and keto acids, while lipids and carbohydrates results in alcohols, esters, aldehydes, lactones and ketones (Preedy and Watson, 2008). The most common volatile compounds of three cultivars are presented in Table 2, but large influence of the cultivar on the quantity of the volatile compounds has been reported (Preedy and Watson, 2008).

Table 2 Volatile compounds quantified in three tomato varieties (Preedy & Watson, 2008).

Volatile compound	Centera (average)	Centera (%SD)	Zucker (average)	Zucker (%SD)	Lucy (average)	Lucy (%SD)
3-methyl-butanal	24.6	26.6	92	16.8	179.2	14.2
2-methyl-butanal	10.9	47.7	65.8	5.5	108	16.1
pent-1-en-3-one	155.7	17.8	295.3	24.1	202.6	4.5
pentanal	47.8	21	52.4	14.3	38.1	4
pentan-3-one	33.9	6.5	48	10.8	33.8	8.6
2-methylbut-2-enal	44.9	64.1	246.1	12.3	349.8	7.6

* Values are the average of three replicates in µg/kg fruit and the standard deviation in percentage.

2.2.6 Color

An important feature for a plant is to successfully spreading its seeds. Therefore, various spreading mechanisms have evolved, including colors and other sensory traits attracting animals in order to get assistance in spreading of the seeds in nature (Hiwasa and Ezura, 2014).

Certain theories are stressing that food attributes have resulted in humans choosing food with attractive colors, due to these often being associated with sensory attributes and maturity stages (Francis, 1995). Based on consumer's preferences, the United States Department of Agriculture (USDA) has selected four factors in tomatoes to determine their quality choice: color 30%, the absence of defects 30%, weight 20% and wholeness 20% (Gould, 1992). Color of the tomatoes has been found to influence perception of also other traits in tomatoes when untrained panelists are used to rank the quality of tomatoes. In general, a positive perception of color resulted in high perception of also other traits such as general appearance, flavor, aroma, and texture (Stommel et al., 2005). For the above reasons, it can be concluded that consumers use color as a major factor in their decision to which type of tomato to procure (López Camelo and Gómez, 2004).

Due to the importance of color for human perception of tomatoes, physiological processes behind the formation of color have reached increasing attention from the research society. The visible changes of color in tomatoes goes from green to bright colors as the tomato matures (López Camelo and Gómez, 2004, Paliyath et al., 2008). The ripening of the tomato can be seen as a combined physiological and chemical process that occurs in the fruit (Paliyath et al., 2008).

Abscisic acid (ABA) and ethylene are the two main plant hormones involved in the ripening process of the tomato plants.(Hiwasa and Ezura, 2014, Zhang et al., 2009). Since tomato is classified as a climacteric plant, the ripening process starts with an abrupt increment of ethylene production resulting in a dramatic change of color, normally from green to red.(Hiwasa and Ezura, 2014, Zhang et al., 2009). In addition, ethylene is accelerating the ripening process of the fruits, simultaneously having a negative impact on the shelf life of the tomatoes (Hiwasa and Ezura, 2014). External applications of ABA have been used to accelerate fruit coloration and softening (Zhang et al., 2009). Furthermore, the application of an external inhibitor of ABA (i.e. fluridone or nordihydroguaiaretic acid (NDGA) was found to delay fruit ripening through the inhibition of ABA production (Zhang et al., 2009).

Besides the plant hormones, temperature is also known to influence the rate of changes of color in tomato. The development rate of red color in tomato is increasing as the temperature increases until 30°C, while higher temperatures are known to inhibit red color development (Nunes, 2008). The physiological explanation of the temperature effect on color change in tomato is reported as an activation and deactivation of certain proteins involved in ripening processes (Neta-Sharir et al., 2005). One type of such proteins are known as heat shock proteins (HSP), being activated under high temperatures, thereby accelerating the ripening process resulting in a skin color change. The specific group of HSP in tomato is designated HSP21 (Neta-Sharir et al., 2005).

Comparing wild type tomatoes with genetically modified ones accumulating a higher level of HSP21 protein, showed an increased expression of HSP21 in the modified tomato at room temperature compared to the wild type tomatoes and the modified type produced HSP21 even at cold storage (2 ºC). The transformed tomatoes developed an orange-red color with an increase of carotenoids after 9 days, despite the fact that they exhibited severe cold injury. Control tomatoes neither displayed changes of color, nor carotenoid accumulation, in these cold conditions (Neta-Sharir et al., 2005). The transformed tomatoes were also found to change from the green stage to the turning stage 7 to 10 days earlier than the control group. However, at similar maturity stage, no differences in carotenoid concentration between the two tomato types were recorded. Thus, a role of HSP21 to promote carotenoids accumulation during fruit maturation was postulated (Neta-Sharir et al., 2005).

The development of color in the tomato fruit during ripening is mainly due to the synthesis of various types of carotenoid pigments, particularly lycopene (90%) and β-carotene (5 to 10%), but also of minor carotenoids, such as lutein and phytoene (Mikkelsen, 2005, Paliyath et al., 2008, Serino et al., 2009). The composition of the carotenoids in the tomato fruit determines the color of the tomato fruits (Ballester et al., 2010). Thus, the change of color in the tomatoes has been highly correlated with the content of lycopene in the red fruit (Stommel et al., 2005 , Preedy and Watson, 2008, Hwang et al., 2016). The β- carotene content is the major determinant of the orange color of tomatoes (Hwang et al., 2016). Pink tomatoes have a transparent peel and is the result of a shortage of naringenin and chalcone flavonoids (Ballester et al., 2010).

Color measurements to understand the skin pigmentation in tomatoes is used as an objective indicator to validate the ripening stage of the tomato fruits. Based on present knowledge it is recommended to validate the color maturity index relationship for each cultivar to succeed in harvesting tomatoes at the optimum level of quality (Beckles, 2012). Traditionally color charts have been applied to determine ripening in tomatoes (López Camelo and Gómez, 2004). However, modern instrument has been introduced and nowadays mainly colorimeters are used to measure color on a numerical base applying the Commission Internationale d'Eclairage L*a*b* (CIELAB) color sphere. CIELAB express color in three coordinates, where L describes the brightness through a scale from white to black, a* measures colors from green (-a*) to red (+a*) and b* those from blue (-b*) to yellow (+b*). For tomatoes the a* is the most representative parameter as a negative value represent green color and an immature tomato, while a positive value rep-resent red color and a mature tomato (Preedy and Watson, 2008). In one investigation, the three color parameters, L*, a* and b*, showed significant changes for tomatoes during ripening, although, some commonly used color components such as chroma (intensity of color), value (darkness of lightness) and hue angle (certain angle in a 360º wheel color), calculated from these parameters, was not suitable for determination of tomatoes ripeness (López Camelo and Gómez, 2004).

Changes of tomato color during ripening and carotenoids content at similar maturity stages have been found highly associated. At the breaker stage of tomato, the a* and b* values are null or negative and carotenoids contents also remain low. At mature red stage, in the tomatoes collected in the field, the a* values increased and β carotene and lycopene synthesis also increased. Finally in ripe red tomatoes, the a* values reached their maximum levels simultaneously as the β-carotene synthesis cease. At this point of ripening, lycopene represent 95% of the carotenoids in all colored tomatoes (Nunes, 2008).

3 Factors affecting quality parameters

3.1 Effects of environmental conditions on fruit quality during development of fruits

3.1.1 Temperature

Temperature affects directly the final size and color of the tomato. The temperature has a large impact on production and accumulation of energy through photosynthesis in the tomato plant that is later translocated to the developing fruits. To reach optimal development of the tomato plant and its fruits, different temperatures are recommended during various stages of the plant development. At the germination stage, the most suitable temperature is 16 ºC to 29ºC, while at the growing stage, the optimal temperature is 18ºC to 28ºC and at fruit set stage it is 14ºC to 24ºC (Jones, 2007).

The highest lycopene and red color accumulation was seen at 24ºC during the day and 14 ºC during the night (Jones, 2007). When the temperature range is between 26º C and 30º C, the TTS content increases due to a switch in enzyme activity and tomatoes also become sweeter (Beckles, 2012). Under Mediterranean conditions, temperature has been shown as a limiting factor for fruit set and yield, and the upper limit being 25ºC to 26ºC (Harel et al., 2014).

In addition, if plants are exposed to temperatures above 30º C, this will induce high evapotranspiration rate and much less carbohydrate biosynthesis will be dedicated for assimilation and sweetness (Beckles, 2012). Therefore, an inhibition of lycopene biosynthesis will occur, promoting a change in color of fruits turning to yellow or orange (Jones, 2007).

3.1.2 Relative Humidity

Relative humidity influences the performance of the tomato plants and fruits. It should be between 30 to 90% (Schwarz et al., 2014) A low relative humidity results in firmer and juicier fruits with a minimum of physical disorders (Xu et al., 2007). Previously, Blossom end rot (BER) has been considered to result from calcium deficiency, however, abiotic stress such as very low relative humidity cause high transpiration rates and accumulation of calcium in the mature leaves, which leads an increase of reactive oxygen leading a risk of fruit disorders such as BER, where the end part of a fruit becomes darkens, flattens out and eventually burn; resulting in cracking (scarfs on tomato skin) and presence of oidium, thrips, spider and mites (Saure, 2014).

A high relative humidity instead promotes low transpiration rates, thereby inducing early growth of leaves with less area due to an increase of stomatal conductance and low calcium accumulation. The latter conditions increase the risk of diseases such as botrytis, mildew, leaf mold (Atherton and Rudich, 2012, Heuvelink and Dorais, 2005, Jones Jr, 2007).

What is to be considered as ideal humidity conditions change due to the development stages. At germination stage, 75 to 88% is desirable; at the seedling stage, 71 to 80% is preferable and from vegetative to termination stages 60 to 80% is beneficial (Jones Jr, 2007). To control humidity, growers use heat and ventilation in controlled environments (Heuvelink and Dorais, 2005) and in arid climates evaporative cooling is used to control the relative humidity (Abdel-Ghany, 2006). Therefore, a relative humidity above 85% combined with high temperature over 30º C become critical for the fruit set. However, to reduce high relative humidity it is recommended to ventilating the greenhouse (Heuvelink and Dorais, 2005).

3.1.3 Light

Light influences performance of tomato plants and fruits, resulting in various quality of tomatoes produced in different seasons. Tomatoes produced during the winter are known to have low TTS compared with tomatoes produced in summer. In addition, tomato fruits under indoor production conditions have lower TTS due to poor light quality as compared with out-door production (Beckles, 2012).

UV light has been shown to influence accumulation of total polyphenol contents in tomatoes. Coffeic acid, ferulic acid and p-coumaric acid contents were found to be about 20% higher in tomatoes grown with UV light (290 to 400 nm) as compared with samples grown under UV restriction (below 380 nm) (Luthria et al., 2006).

3.1.4 Soil nutrients

The tomato plant has a high demand of nutrients. Nitrogen, phosphorus and potassium are the major macronutrients used at tomato plant cultivation. Excess or deficiency of one or more of these nutrients are known to impact negatively on fruit quality (Beckles, 2012).

Macronutrients: Nitrogen, phosphorus and potassium

According to previous studies, N supply has been found to affect TSS in tomato, although various impacts have been reported. Thus, reduction of nitrate from 12 mM to 4 mM was found to increase TSS concentration (mainly sucrose, fructose and glucose), reduce acidity, while yield was not affected. However, studies in cherry tomato treated with 0 to 36 mM of nitrate, showed instead a high and positive correlation between nitrate addition and TTS concentration and here nitrate concentrations above 9 mM TSS also affected negatively the yield (Beckles, 2012).

Effects of potassium and phosphorus have been also studied. High concentrations of potassium lead to an increase in TSS concentration. However, this increase may also be related to an increase in electrical conductivity (EC), due to the fact that concentration of these nutrients, soil water content and salinity is interacting (Beckles, 2012). In addition, type of nutrient source, e.g. liquid or solid fertilizer, may impact absorption by plants (Beckles, 2012). Total amount of carotenoids, and in particular of lycopene in tomato fruit, is generally positively correlated to the amounts of potassium available for the tomato plant (Mikkelsen, 2005).

Salinity

Salinity in a range of 2.5 to 14 dS m-1 electrical conductivity (EC) has a positive impact of sugar contents of tomato fruits (Cuartero and Fernández-Muñoz, 1998). Manipulation of salinity affects the internal metabolism of the tomato plant by impacting the length of time for development and maturation, Thus, increase in salinity to a certain degree leads to a higher TSS (Beckles, 2012). However, this change has a yield cost of 10% of reduction for each 1 dS m-1, from 8 dS m-1to 14 dS m-1, and a higher concentration of salts (EC of 15 dS m-1) reduced the number of fruits as well (Cuartero and Fernández-Muñoz, 1998).

Nutrient deficiency

Nutrient deficiency in the soil severely reduces tomato quality and yield. Lack of major nutrients, such as potassium, causes non-uniform ripening color of the tomato fruit (Haifa, 2014). Furthermore, an increase of photosynthesis was associated with potassium deficiency, and symptoms such as diameter expansion of the stem could be detected, although such changes were only noticed late in the plant development (Kanai et al., 2011) Calcium applications have been found increasing firmness of the tomato (Magee et al., 2003).

Several studies have compared the performance of organic and inorganic production systems in order to determine how these affect quality parameters. In general, contradictory results have been presented as to how different production systems are affecting the TSS. In order to elucidate effects on nutrient contents in the different systems, further studies are needed (Beckles, 2012).

3.1.5 Size

The size of the tomatoes depends on the genetic background, the cultivation location of the plant and on cultural practices. During fruit set, cultural practices such as pruning have a direct influence on the tomato fruit size. Through the reduction of the number of buds, the number of fruits is reduced, and therefore an increase of size of the tomatoes left on the plant is likely the result (Beckles, 2012).

3.2 Current post harvest management of tomato

A variety of methods are used to extend the shelf life of tomatoes (Preedy and Watson, 2008). One major opportunity to impact both edibility and marketability of the tomatoes is to control the synthesis and action of the plant hormone ethylene. Methods used to control this hormone includes application of innocuous products on the surface of the tomatoes, decrease of storage temperature, application of modified atmosphere packing or combination of these methods (Gross et al., 2016).

3.2.1 Temperature treatments and their implication on shelf life, appearance, color, firmness, chilling injuries and bioactive compounds

Low temperature treatment of tomatoes contribute to a reduction of the ripening processes, thereby slowing down changes in texture, aroma, flavor and nutrition contents, and stopping changes of color. After removing tomatoes from low temperature treatment, light red tomatoes are able to change color to dark deep red (Paull, 1999). However, immature tomatoes are more sensitive than mature ones to low temperatures. Thus, immature tomatoes might be harmed by low temperatures and develop chilling injuries such as decrease of volatile contents, high increase of softness as a result of loss of cell turgor, and abnormal ripening progress resulting in non-uniform red color in full ripening stage (Nunes, 2008, Passam et al., 2007). Besides chilling injuries, tomatoes treated with low temperatures develop less intense color as compared with fully ripe tomatoes in the field (Nunes, 2008).

One opportunity is to combine different temperatures during storage to enhance quality. Thus, treatment of fully ripe tomatoes with low temperature of 2 ºC to 5 °C for short periods, before they are transferred to a temperature of 20 ºC, results in an increase in shelf life for the tomatoes due to a decrease in natural decay processes of the fruit. Combining temperatures of 9 °C during six days and then change to 20 °C for one day, prevented against pitting in tomato (Nunes, 2008).

Shock temperature treatments have also been used in tomatoes to increase resistance towards pests and decrease the chilling injuries from later cold storage. One example of such treatment is a hot water dipping in 52 °C for one minute, which was found to prevent against chilling injury and botrytis attacks (Fallik et al., 2002). In another study, a short heat treatment before low temperature storage reduced fruit cracking under modified atmosphere packing (MAP) and delayed color development in cherry tomatoes (Ali et al., 2004). However, a too high temperature, or duration of the heat treatment, results in heat injury, with irregular color during ripening, development of decay, brown spots and cracking. Tomatoes exposed to 38 °C for 24 hours showed severe injuries (Nunes, 2008).

3.2.2 Application of organic substances after harvest to improve or extend shelf life of tomato

Applications of organic compound, such as methyl jasmonate and methyl salicylate, reduced chilling injury and promoted the gene expression of heat shock proteins. Both compounds are also related to plant defense response (Ament et al., 2010).

Coating gum arabic on green mature tomatoes increased shelf life up to 20 days by reducing ripening rate at 20ºC and also maintained the overall quality (Ali et al., 2010). Amino acid aminoethoxyvinylglycine (AVG) treatment at 30 kPa vacuum infiltration enhanced firmness and increased shelf life of tomato fruit to 20 days at 12 ºC (Candir et al., 2017). On the other hand, other compounds promote acceleration of ripening, such as application of melatonin (50 uM) in a postharvest treatment, which increased lycopene level as compared with a control group (Sun et al., 2015).

3.2.3 Application of inorganic substances after harvest to extend shelf life of tomato

The most common pathogens attacking tomato after harvest are (Gross et al., 2016):

- *Alternaria. alternata*
- *Colletotrichum spp*
- *Clavibacter. michiganensis*
- *Pseudomonas syringae*
- *Xanthomonas campestris*
- *Fusarium spp,*
- *Botrytis cinerea*
- *Phytophthora. infestans*
- *Phoma lycopersici*
- *Phomopsis spp*
- *Phytophthora spp*
- *Stemphylium herbarum*
- *Rhizopus spp*

- *Sclerotium. rolfssi*
- *Rhizoctonia. solani*
- *Geotrichum candidum*
- *Sclerotinia spp.*

To prevent against attack from these pathogens and thereby preserve the quality of the fruits, inorganic substances e.g. chlorine in a concentration of less than 100 ppm, are used during the packing sanitization process. Chlorine eliminates certain gram-positive and gram-negative bacteria, yeast and molds, as well as spores and viruses (Gross et al., 2016).

Currently, research on tomato is based on maturity stages to apply different strategies to extend the shelf life of this commodity. Maturity stages are characterized as follow (Zhang et al., 2009).

Stage 1: mature green (approximately 40 days after anthesis,
Stage 2: breaker 1 (approximately. 44 days after anthesis)
Stage 3 breaker 2 (approximately 45 days after anthesis)
Stage 4 Turing (approximately 46 days after anthesis)
Stage 5 Pink (approximately 50 days after anthesis)
Stage 6 Mature red (approximately 53 days after anthesis).

A short application of calcium chloride at 1%, combined with boric acid at 0.1%, on mature green tomatoes then packed in polyethylene film (0.44mm thickness) was found to slow down the ripening rate, maintain firmness, weight, color, and increase TSS and TA. Thereby, this treatment extended the shelf life of the tomatoes to 72 days while stored at 28º to 30ºC (Sammi and Masud, 2009).

Active paraffin-based paper packing combined with Barck cinnamon essential oil (6% w/w) promoted a total inhibition of *Alternaria alternata* in cherry tomatoes. In the same study, other parameters such as color and weight did not differ as compared with the control (Rodriguez-Lafuente et al., 2010).

Granular active carbon combined with palladium (1%) in modified asthenosphere packaging (MAP) and cold storage, reduced softness, weight loss, delayed tomato decay and reduced expression of 23 volatile compounds as compared with the control. In addition, when the packages were opened, the treated tomatoes showed improved odor intensity compared with the control, as ranked by panelists. However, the use of palladium has been reported to significantly increase allergic reactions in sensitive humans. Therefore, granular active carbon under MAP conditions have also been evaluated, excluding the treatment with palladium, resulting in only 65% of decay compared with 100% in the control tomatoes after 28 days. Thus, granular active carbon without palladium is a suitable method to extend shelf life of tomato (Bailén et al., 2006, Kielhorn et al., 2002).

Artificial applications of organic molecules have diverse effects on postharvest fruit physiology. Ethylene is an organic compound formed naturally as a plant hormone in tomato. It is responsible for major changes in physical, chemical, physiological and biological properties. Those changes affect sensory traits in tomato during the ripening process, independent if the fruit is attached or not to the plant. Ethylene is known to affect the firmness, flavor, color and bioactive compound levels (Preedy and Watson, 2008). Since ethylene accelerate ripening, an inhibitor called 1–methylcyclopropene (1-MCP) has been tested in order to delay ethylene effects on tomato fruits. One result from such an evaluation of the use of 1-MCP showed a change in lycopene concentration at the break stage (Opiyo and Ying, 2005). The use of 1 µL L-1 1-MCP for 24 hours, delayed fruit ripening, reduced respiration rate and inhibited ethylene production after 20 days at 20ºC and 85 to 95% of RH (Wang et al., 2010a).

3.2.4 UV light application on tomato and impact on shelf life

During the last years, use of ultraviolet (UV) light has become an attractive alternative method to improve tomato quality and shelf life. The suggested reason for the positive effects reported from this treatment is that it triggers biochemical defense reactions in the tomatoes, but also that fruits and vegetables are sanitized by the use of UV light (Ribeiro et al., 2012). The use of *Chryptococcus laurentii* combined with UV-C was found to eliminate infection *of Botrytis cinerea* and *Alternaria alternata* (Zhang et al., 2013). Further, the same doses of UV-C application delayed tomato softening due an inhibition of ethylene production in mature green cherry tomatoes (Bu et al., 2013). Other parameters such as color, pH and Brix did not show any differences as compared with the control, when UV-light was applied (Pataro et al., 2015).

Molecular studies performed to understand the genetic molecular mechanism from application of UV- C revealed that 274 genes were upregulated and 403 were downregulated. Upregulated genes were responsible to target the defense response system, signal transduction and metabolism, and downregulated genes were involved in photosynthesis, lipid metabolism and cell wall disassembly. These results may explain the increased disease resistance in treated tomatoes (Liu et al., 2012).

3.2.5 Application of modified or controlled atmosphere using carbon dioxide, oxygen, nitrogen and ozone treatment and impact on shelf life

Modified atmosphere (MA) or controlled atmosphere (CA) were both shown to reduce ethylene concentration and thereby retard maturation of tomato fruits. Generally, increased carbon dioxide concentration and decreased oxygen concentration results in a reduction in respiration rate and ethylene synthesis. The most suitable levels to extend shelf life of fresh tomatoes are 3-5% oxygen, 1-5% carbon dioxide and 94-96% nitrogen. Such a modified atmosphere does not affect the TSS content (Beckles, 2012).

Modified atmosphere packing (MAP) was adopted to ensure modified atmosphere conditions in smaller scale. Different types of low density polyethylene films are applied for the MAP, which then constitute a barrier between the general atmosphere and the atmosphere in the package. This barrier is made of different types of low density polyethylene package (Beckles, 2012). Generally, MAP creates an artificial atmosphere and permits a moderate gas exchange with the outer atmosphere. By the use of MAP, shelf life of tomatoes increased through a retarded respiration processes, reduced water loss, less disease attacks, and less bruising (Beckles, 2012).

The use of ozone enriched atmosphere resulted in tomatoes with increased firmness (Tzortzakis et al., 2007, Rodoni et al., 2010), and additionally the tomatoes have been judged sweeter as compared to control tomatoes (Beckles, 2012). This treatment did not affect weight loss, antioxidant status, ethylene production and vitamin C concentration (Tzortzakis et al., 2007). Ozone treatments were also shown to result in reduced attacks of microorganisms (Beckles, 2012), decreased activity of the pectin-methyl esterase (PME) enzyme, weight loss and fruit damage as compared to the control (Rodoni et al., 2010). In addition, ozone reduced solubilization and depolymerization of pectin polysaccharides (Rodoni et al., 2010).

3.2.6 Mechanical technologies in postharvest management of tomato

Novel methods are emerging to be used on tomatoes to increase quality and shelf-life, e.g. inert treatments such as ultrasounds and thermosonication (Pinheiro et al., 2016). The use of ultrasound was found to change the microstructure of epidermis, resulting in brighter and a more orange color of the treated tomatoes (Fava et al., 2017).

3.3 Effects of postharvest techniques on fruit quality traits

Quite a number of studies have been carried out to understand how post-harvest conditions are affecting the tomato fruit quality and how the quality can be improved through different treatments. Below effects of post-harvest treatment on various parameters are described.

3.3.1 Texture

As mentioned above, a combined treatment applying calcium chloride at 1%, boric acid at 0.1% and 400 ppm of potassium permanganate on green tomatoes, followed by packing in polyethylene film, increased shelf life up 32 days and improved and overall quality characteristics of tomatoes, but this treatment also improved the texture (Sammi and Masud, 2009). Also, treatment with 7.5 ppm of potassium permanganate preserved texture at 14 to 18 ºC after 21 days (Wabali et al., 2017). Another study showed that pulse light treatment at 4, 6, and 8 J/ cm^2 fluence time did not affect the texture after 10 days of storing although microbial growth was reduced (Valdivia-Nájar et al., 2018). Furthermore, hot air treatment during 12 hours at 38ºC on mature green tomatoes delayed firmness decline, due to slowdown of pectin degradation (Wei et al., 2018).

3.3.2 Flavor and volatile compounds

For postharvest storage of tomatoes, a common method applied is the use of modified ambient conditions which greatly affect flavor and volatile compounds. Storage of tomatoes under nitrogen was shown to reduce the amount of C6 volatile compounds in the stored tomatoes, as did storage of the tomatoes at low temperature, 6

°C for three days. Returning the tomatoes to normal conditions, did not result in a full recovery of the content of volatile compounds (Boukobza and Taylor, 2002). Refrigeration or short treatment with high temperature affected negatively and irreversibly the content of volatile compounds (Nunes, 2008). However, according to recommendations from University of California, chilling injury occurs at temperatures below 10 ºC if held longer than two weeks, and recommended temperatures are between 7 Cº and 15ºC depending of maturity stage and length of storage time (Suslow, 1997)

A continuous treatment of green tomatoes with 3% to 5% of oxygen and 0% of carbon dioxide at 13 ºC for 6 weeks resulted in more acid flavor of the tomatoes (Parsons et al., 1970). Flavor volatiles are generally affected by storage temperatures due to the alteration of the volatile synthesis. The content is reduced at low temperatures, while partly recovered after transfer to 20 ºC, although the flavor is still reduced (Zhang et al., 2016). Coating tomatoes with arabic gum or beeswax plus sodium bicarbonate at 2%, resulted in maintained flavor under low temperatures (Fagundes et al., 2015). Also, the above mentioned application of a solution of boric acid at 0.1% and calcium chloride at 1% on green tomatoes followed by packing with polyethylene film resulted in a maintained flavor at storage of 28º to 30ºC (Sammi and Masud, 2009).

3.3.3 Total soluble solids and titratable acidity

Tomatoes ripened on the vine have higher levels of TSS due to a higher importation of sugars from the plant to the fruit during this stage (Nunes, 2008). Therefore, it is highly recommended to harvest during the mature green or breaker stage to reduce the negative impact on TSS and TA and the consequently lower quality and less pleasant taste (Beckles, 2012).

Both TSS and TA were found increased after a heat pulse treatment between 37°C to 42 °C, followed by 14 °C in storage room conditions (Beckles, 2012). A combination of continuous oriented polypropylene (OPP 30µm thick) and perforated holes smaller than 2 mm, preserved better TA, TSS and vitamin C concentration in tomatoes due to reduction, but not inhibition, of CO_2 levels at 20 ºC and $\leq$ 90% RH (D’Aquino et al., 2016). Green mature tomatoes exposed at a concentration of 1 µL L^{-1} of 1-MCP for 24 hours, followed by storage at 20 ºC and 85 to 95% of RH for 20 days resulted in maintained firmness, TSS and TA (Wang et al., 2010b). Short enrichment with ozone enhanced sugar content and acidity (Rodoni et al., 2010)

3.3.4 Treatments effecting fruit color during the ripening process

A combination of oxygen (O_2) and carbon dioxide (CO_2) content can be used to delay ripening and therefore color change of tomato. For red tomatoes 3% CO_2 and 2% O_2 was reported optimal (Wills, 1998) while for mature green tomatoes 3% to 5% of CO_2 and low O_2 was preferential, extending shelf life with 6 weeks without any off flavors (Parsons et al., 1970).

Ultrasound was found to change the microstructure of epidermis, resulting in that the tomatoes became brighter and conferred a more orange color compared to untreated tomatoes (Fava et al., 2017).

Phospholipase D is an enzyme that activates the deterioration system of the cell membrane in tomatoes, thereby contributing to the ripening process. Lysophosphatidylethanolamine (LPE) is an inhibitor of this enzyme and can be used to increase shelf life and preserve quality of tomato (Amalendu et al., 2003).

The plant hormone abscisic acid (ABA) is known to promote ethylene synthesis and thereby induce ripening, resulting in tomatoes turning red faster. The inhibitors fluridone or nordihydroguaiaretic acid (NGDA) are reducing the ABA production, and thereby delaying fruit ripening and color development of tomato fruits (Zhang et al., 2009).

The amino acid aminoethoxyvinylglycine (AVG) suppress ethylene production in plants, and consequently delays fruit ripening (Boller et al., 1979). Furthermore, AVG enhances fruit firmness and has thus a potential use in postharvest management (Rath and Prentice, 2004). AVG was shown to postpone the natural ripening process by 10 days through a lowering of ethylene production, lycopene color values, and a* and C* values (Candir et al., 2017).

Temperature during storage is known to influence the color of the tomatoes. Table 3 summarizes the relationship between storage temperature, numbers of days treated in a certain temperature, change in color related to human perception, and changes in color, using a colorimeter in fresh tomatoes.

Table 3. Relationships between storage temperature and change in color.

Storage temperature	Number of treatment days	Change in color (human perception)	Change in color (colorimeter)	Reference
10, 15 or 20ºC	Unknown		Color increased slightly regardless of the temperature	(Proulx et al., 2001)
10, 15 or 20ºC	Unknown	Change	L* decreased during storage	(Proulx et al., 2001)
20ºC	Unknown	From turning to red	L* decreased gradually from 50.8 to 42.7	(Nussinovitch et al., 1996)
20ºC	7		L* value decrease after 7 days	(Auerswald et al., 1999)
20ºC	12	Mature-green to full ripe	Linear increase in a*/b*	(Giovanelli et al., 1999)
37ºC	12	Yellowish color	Increases in L*, b* and chroma values and decreases in a* and hue	(Gnanasekharan et al., 1992)

* Hunter's values a* b* and L*; color index a*/b* (ratio of red to green component).

3.3.5 Change in nutrients and nutrient contents

Treatments of tomatoes with UV-C, with an average of 4 kJ m^{-2}, increased, up to 20%,the concentrations of phenolic compounds, such as gallic acid, chlorogenic acid, syringic acid, p-coumaric acid and quercetin; enhanced accumulation of antioxidants; organic acids; ascorbic acid; lycopene and total carotenoids. Furthermore, a sensory panel gave higher rates on taste and quality of treated tomatoes as compared to control (Beckles, 2012, Liu et al., 2012, Charles et al., 2016). Therefore, the application of this interval of light has been suggested to enhance accumulation of healthy compounds in tomatoes (Pataro et al., 2015).

Also, methyl jasmonate was found to increase antioxidant levels in tomatoes simultaneously as the resistance to diseases during cold storage was promoted (Ding et al., 2002). An application of 1 MCP for 24 hours followed by storage at 20 ºC for 20 days contributed to increased ascorbic acid and soluble phenolic contents (Wang et al., 2010a).

Furthermore, ozone enrichment was found to enhance phenolic compounds accumulation and antioxidant capacity in tomatoes (Rodoni et al., 2010). Ultraviolet radiation preserved higher quantities of total phenolic content, tomatoes had lower water loss and showed a decrease in bacterial presence after treatment (Pinheiro et al., 2016).

3.4 Reduction of losses

Food loss and waste in the food chain occur during agricultural production, post-harvest handling, storage, processing, and also during distribution and consumption (Porat et al., 2018).

3.4.1 Reduction of losses by the use of pre-harvest factors

Variation of environmental conditions, such as soil, climate, season, geographic position, production in greenhouse or open field under different fertilization systems, are affecting the tomatoes quality parameters e.g. color, size and weight (Beckles, 2012). To avoid losses in the production, several methods have been developed: e.g. adequate application of pesticides may reduce postharvest losses (FAO, 1989). In rainy areas, high furrows are a common practice to avoid over watering and flooding.

A careful and well-planned crop management, including the use of fertigation and proper watering together with the addition of auxin (a plant regulator) contribute to an increase in fruit production and fruit size, a reduction of losses and a faster ripening process (Oda and Saito, 2006).

Another common strategy to prevent losses is the use of greenhouse production, which also satisfies the internal demand for fresh tomato consumption in off season. Also, in field production, plastic tunnels can be used to control ripening during the low temperature season. In the greenhouse, forcing, semiforcing, and late raising are commonly applied to induce proper growth and maturity of tomatoes (Oda and Saito, 2006).

3.4.2 Reduction of losses during postharvest handling

To prevent damage during harvest or transport, a complex combination of technology, pest management, marketing and distribution systems are used to reduce postharvest losses (FAO, 1981). To reduce losses it is important to understand the different sources of the postharvest losses. For example, a comparison between commercial farmers and subsistence farmers elucidated the main sources of post-harvest losses; i.e. market price stability (29%), logistic control activity (21%), and quality control activities (23%). Farmers with advanced logistics, high activity and quality controls combined with a stable market (70%) showed in general lower postharvest losses as compared with subsistence farmers who work in vulnerable context, use basic logistic, perform low quality control and have limited access to the formal market (only 8%) (Macheka et al., 2018).

Simple practices before transportation e.g. washing, sorting and the use of clean plastic package were shown to reduce aerobic bacterial count (ABC), coliform bacterial count, yeast and mold by 2.51%, 32.7% and 29.86% respectively, as compared with the control (Khadka et al., 2017). During transport, forced-air cooling (FAC) or pressure cooling (PC) are the most efficient cooling methods in a dry climate (Sargent, 1998). In general, most of the existing problems related to postharvest losses in tomatoes can be handled with the current available technology and information (Kader, 2005). Thus, a combination of modified atmosphere packages together with application of aloe gel were found to increase lycopene, phenolics, and ascorbic acid contents, while microbial counts were reduced at 16 days of storage. However, a longer period between harvest and consumption resulted in a reduced natural flavor of the tomatoes (Mirdehghan and Valero, 2017). Parameters related to nutritional aspects and flavor have in general shorter durability as compared with parameters traditionally used to decide shelf life (Kader, 2008).

Regarding socioeconomic aspects, application of postharvest management can have a positive economic impact on growers, reduce their poverty, and provide food security and a positive effect on sustainable use of resources (Kader, 2005). National initiatives organized by public agencies may reduce postharvest losses. For example in Japan, the Ministry of Agriculture released cultivars resistant to fruit malformation, strips, and less susceptible to cracking (Oda and Saito, 2006). In addition, the use of high technology during selection and well-designed packaging protecting the final product, which was combined with an organized logistic solution, including cold chain management and retail packaging, resulted in improved tomato quality and reduced losses (Porat et al., 2018).

3.4.3 Biochemical changes caused by mechanical damage

Different pre and post-harvest conditions may cause mechanical damage, but particularly after harvest large injuries may occur, which lead to reduction in TSS and TA contents (Beckles, 2012). Causes of the mechanical damage in tomato fruits are impact damage, compression, abrasion and puncture. Impact damage and compression cause bruising and cracking damage, abrasion affects visual perception and color, depending of the maturity stages. Tomatoes may be injured by puncturing objects such as stems from others tomatoes, perforating skin surface during harvest, storage or packing (Li and Thomas, 2014). At the cellular level this may result in cell lysis and several undesirable chemical reactions such as accel-erated transpiration, respiration, ethylene production and pathogen infestation (Beckles, 2012). Mechanical harvest increased pectin methylesterase (PME) activity and increasing softness as compared with hand harvest. Tomatoes exposed to 40º C or higher temperatures became more damaged and soft. However, these conditions promoted better juice consistency after processing as compared with tomatoes stored at lower temperatures (Held et al., 2015).

4 Genetic studies in tomato

4.1 Genetic studies related to biodiversity using molecular markers

Tomato genetic biodiversity studies provide information on the genetic identity, genetic relationship, genetic diversity and genetic distance among accessions of tomatoes, information obtained primarily through the use of different types of molecular markers (Parmar et al., 2010). Genetic studies are often applied to discriminate biodiversity within and between commercial and wild species of tomatoes and their relatives (Passam et al., 2007). Genetic variation can be seen as a natural variation, which depends on the presence of different alleles and their frequency (Wray, 2008). Polymorphism for different alleles has been found to be low in cultivated tomatoes due to self- pollination and a narrow genetic base. On the contrary, genetic distance and polymorphism of wild tomato relatives (*L. peruvianum, L. pennellii and L. hirsutum*) have been found high. These wild tomatoes thereby constitute an enormous source to improve quality traits, as well as biotic and abiotic resistance of cultivated tomatoes (Passam et al., 2007).

By the use of 165 SSR (simple sequence repeat) markers, four main clusters were found among eight tomato cultivars, indicating the use of SSR markers being a cost effective method for diversity evaluation studies (Kwon et al., 2009, Todorovska et al., 2014). Generally, simple sequence repeats (SSR) and retrotransposon based sequence specific amplification polymorphisms (SSAP) have been shown to be more accurate than randomly amplified polymorphic DNAs (RAPDs) to determine genetic variation in tomatoes (Passam et al., 2007). The use of single nucleotide polymorphisms markers (SNPs) has shown wild tomatoes having a 20–fold higher variation than cultivated crop accessions, indicating genetic erosion among cultivated tomatoes. In addition, a correlation between geographical location and growth habit of the tomatoes has been reported (The Tomato Genome et al., 2012). Currently, next generation technique (NGT) is reported as the most powerful technique to identify DNA sequence polymorphisms and create molecular markers to use in plant breeding programs (Devran et al., 2018). Biodiversity studies within populations is highly important, providing new information to breeders to develop cultivars with genetic tolerance or resistance to biotic and abiotic problems in tomato (Parmar et al., 2010).

4.2 Genetic studies related to quality parameters using molecular markers

The genetic map of tomatoes is a valuable tool, contributing to opportunities for identification of chromosomal regions responsible for certain quantitative or qualitative traits. The understanding of location of various genes can combined with traditional plant breeding techniques result in the introduction of desirable characteristics into commercial cultivars (Devran et al., 2018). Important quality traits of tomatoes can either be controlled by a single gene or by quantitative trait loci (QTL), were several minor genes are combined to determine the trait. Domestic tomatoes have a high variability in fruit shape as compared with the wild types and this trait has been found controlled by QTLs. Actually, tomato traits like shape, color, size, ripening, organoleptic quality, pollination, field diseases resistance as well as resistance to abiotic factors, such as chilling temperatures, are all known to be controlled by QTLs (Passam et al., 2007).

4.2.1 Nutrient contents and sensory factors

Wild tomatoes provide a potential resource for breeding of tomatoes with increased nutrient content. The *Solanum* L. c*heesmanii* is one species naturally holding high β-carotene and sugar contents, while the *Solanum* L. *peruvianum* Mill is a source of aromatic fragrance (Passam et al., 2007). A study on recombinant inbred line (RIL) crossing *S. lycopersicum* and *S. pimpellifolium*, demonstrated that both parents contribute to the genetic variation among the progeny for content of calcium, copper, iron, magnesium, manganese, sodium, phosphorus sulfur, strontium and zinc meaning that a plant breeding program may use this information to seek to increase contents of those minerals (Capel et al., 2017).

Studies on heritability can be carried out in tomatoes using Restricted maxi-mum likelihood estimation (REML), where genetic heritability represents similarities between parents and their offspring, and a mathematical mixed model with fixed effects and random effects are used for the calculation (Wray, 2008, Hall and Bush, 2016). A recent study on tomato using REML demonstrated that amino acids were shown to have higher and stable heritability (0.57) as compared with the heritability of volatile compounds (0.39) during a period of 2 years. In the same study, the phenotypic heritability was found ranging between 0.28 and 0.77 while the genetic heritability ranged between 0.11 to 0.82. The genetic and phenotypic heritability were also found to have low correlation. Using genome-wide association studies, eleven associated traits of amino acids, acids, sugars and volatile compounds were consistently detected through two years in chromosomes 1,4, 6, 8 and 9 (Bauchet et al., 2017).

An over-expression of malate in transformed tomato plants was found to affect a number of post-harvest quality traits, including water loss and wrinkling; TSS content, and resistance to opportunistic pathogen infection (Centeno et al., 2011).

4.2.2 Texture and yield

A disassembly of polysaccharides leads to fruit softening and specific enzyme activities are highly correlated with these changes. Through the use of transgenic tomato, a gene related to pectatelyase (PL) was silenced, which resulted in a severe change in tomato fruit texture and softening of the fruits. PL reduction significantly increased fruit firmness, maintained the fruit integrity longer than in the control but showed no effect on yield, weight, ethylene biosynthesis, color or TSS. In addition, an increase of thickness and density of tricellular junction zones as well as a prolonged shelf life was observed while the PL was silenced (Uluisik et al., 2016)).

4.2.3 Color

An impressive amount of diversity in color exists naturally in tomatoes, and some types of tomatoes even retain their green color, meaning that they never change color to red and ripe. To understand the genetic background for such differences in processes is important while designing breeding programs for tomatoes. Through the use of real time PCR to evaluate mutants of tomatoes, changes in enzyme activity associated with cell wall disassembly have been demonstrated as a reason for the colorless non-ripening behaviour. Expression of cell wall degrading enzymes such as polygalacturonase, pectinesterase, galactanase and xyloglucan endotransglycosylase was dramatically reduced in mutants unable to change color and maturate. On the contrary, higher levels of the enzyme pectinesterase were detected in non-ripening wild cultivars as compared with the levels in the mutant. Thus, a link between events during ripening controlling cell separation in cell walls of tomato and those involved in the formation of dehiscence zones in dry fruits, was postulated (Eriksson et al., 2004).

The table below presents a summary of tomato genes known associated with color (Rick, 2017). Some genes, such as the chrysanthemum sterile, are affecting orange, red and brown color. Others genes are known to influence color more specifically. For example, the gene tangerine, on the arm L in chromosome 10, controls the orange color trait (Rick, 2017). The gene CYC-B (77 SNP) is known to confer orange color to tomatoes and this gene has also been shown to correlate with the abundance of β-carotenoids (Hwang et al., 2016).

Table 4 List of genes associated with color traits in tomato flesh fruit (Rick, 2017).

Gene	Allele	Gene name	Phenotype
chrs		Chrysanthemum sterile	Red fruit brown sectors
hp2	j	High pigment 2	Red fruit
B	og	Beta carotene	Orange
chrs		Chrysanthemum sterile	Orange
Del		Delta	Orange
Dps		Dispyros	Orange
Nr		Never ripe	Orange
T	2	Tangerine	Orange
Vo		Virescent Orange	Orange
ant		Aurantia	Orange
aur		Aurantiaca	Orange
K		K	Yellow
r	2s	Yellowflesh	Yellow
mic		Minuscula	Yellow
abi		Aubergine	Purple
chrs		Chrysanthemum sterile	Brown color
gf		Green flesh	Brown color
dg		Dark green	Dark green

5 General Conclusions

The tomato crop is a highly important horticultural product in the world. The consumption is global and thanks to advances in research, an increasing number of places are suitable to produce tomato in open fields or in the greenhouse with different climate conditions. In addition, studies on native germplasm have become increasingly important, as these are contributing to our understanding of lost quality traits in commercial cultivars, such as resistance to rough climate conditions. Further, he majority of the resistant quality traits also influences the yield negatively.

The main quality parameters, such as textural properties, aroma, volatile compounds, flavor, total soluble solids, titratable acidity, and color are used to classify tomatoes. Most of these parameters are highly affected by temperature, relative humidity, light, soil nutrients and the size of the cultivar during fruit production. A deeper understanding of the relation among the mentioned traits and their interaction with the environment will facilitate the development of methods to preserve or improve the quality parameters of tomatoes.

Postharvest management, such as the application of organic and/or inorganic substances, or modified atmosphere packing, contributes to a pro-longed shelf life, prolongs the window for distribution s of quality tomatoes and preserves the quality parameters of the tomato.

Recent studies have clearly shown the importance of reducing post-harvest losses in tomatoes. Reasonable living conditions of farmers and use or adaptation of technology, logistics and preservation of quality parameters in all parts of the chain from production to consumers are important factors to secure low post-harvest losses

In conclusion, this introductory paper shows the presence of a large amount of knowledge, based on traditional as well as on modern and powerful technology. A huge and deep understanding is available of the tomato plant and its interaction with the environment, nutrient conditions, management and effects on quality traits. However, there are still important gaps of knowledge of the role of certain secondary metabolites and their potential impact on the tomato plant or human health.

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