The Effect of Industrial Food Processing on Potentially Health-Beneficial Tomato Antioxidants

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Increasing desires from both consumers and producers to understand better which nutritive components are present in our food and how these are influenced by industrial processing strategies is resulting in extra research involving the use of state-of-the-art technologies to generate novel biochemical information. In this review, attention has been focused on tomato as this is a product eaten right across the world both as fresh produce and after having been processed in a wide variety of ways. There is a particular interest in tomato as it is a major component in the so-called “Mediterranean diet” which has recently been associated with a healthier lifestyle. Tomatoes are rich sources of a variety of nutritional compounds and especially some key antioxidant components such as the carotenoid lycopene, vitamin C, and a range of polyphenols. The potentially protective properties of these antioxidants are of great interest and the consumer has already become aware of their potential importance. Surveying the literature has revealed that much research has been done on the biochemical composition of tomato and its products. However, it remains difficult to make clear conclusions on optimizing the processing strategy. Many, apparently conflicting, findings have been reported and consequently, in this review, we have drawn attention to these and have attempted to clarify their cause. Finally, a range of recommendations has been made as to how future research might be performed in order to generate more concrete conclusions enabling recommendations towards more optimized processing strategies.

Keywords tomato, antioxidants, food processing, metabolomics, health beneficial compounds

INTRODUCTION

There is a broad and growing interest in knowing more about the quality and nutritional value of the food we eat. Consumers are consequently, becoming increasingly critical about which products are bought in the supermarket. Industry is becoming more aware of these trends and has a general desire to meet, where possible, consumer demands when it comes to providing both the information and the products needed to meet current needs. The so-called “Mediterranean diet” is recognized as being particularly healthy—especially in comparison to other diets typical of Northern European and American consumers (Keys, 1995; Willett et al., 1995). A key component of this diet is tomatoes and processed tomato products. In this review, an overview is provided of the (often contrasting) findings recently reported on the biochemical composition of these fruits and how this is influenced by both genetic and external factors. In addition, the opportunities which new analytical approaches, such as metabolomics, may provide in advancing our knowledge in this area, is discussed in the context of a general desire to optimize food composition.

The nutritional value of tomato products is a topic attracting much attention, particularly regarding the effects resulting from food processing and storage treatments. Those nutritive
compounds showing antioxidant activity are of particular interest due to their perceived health-promoting benefits (Hollman et al., 1996; Clinton, 1998; Rao and Agarwal, 1999; Agarwal et al., 2001; Bugianesi et al., 2004; Campbell et al., 2004). The starting point for optimally retaining the tomato's nutritional properties during processing is the raw material. Hence, suboptimal conditions for fruit transport and storage must be avoided. Most of the components in tomatoes are stabilized in vivo by the acidic pH of the fruit tissue, and many nutrients are also conserved during relatively short and mild processing steps. During transport and storage, intact fruits and vegetables are prone to deleterious changes induced by respiratory, metabolic and enzymatic activities, as well as by desiccation, pests, microbial spoilage, and temperature-induced injury. Many of these changes adversely affect the antioxidant status of the tomato products (Lindley, 1998).

The antioxidant capacity of tomato end-products often changes when more invasive processing steps are used (Powell and Bennett, 2002). The greatest attention should therefore be given to minimizing the detrimental effects of these processing methods and the subsequent storage conditions used. Processed products undergo interventions which have considerable potential to result in adverse effects (see below). Nevertheless, in contrast, there are also recent studies which have shown that compounds having antioxidative effects, such as lycopene or β-carotene may also be increased as a result of food processing (Chen et al., 2000; Graziani et al., 2003; Chang et al., 2006). Total antioxidant capacity may also increase or decrease. It will become clear that recent literature is strewn with such apparently conflicting examples of the fate of tomato materials during processing. Deciphering the biochemical basis of these apparently contrasting reports is a key topic of this review.

Elucidating the extent of biochemical changes during industrial processing and understanding exactly which components are affected, are of critical importance in optimizing industrial processing methods/steps and conditions. Although the effect of processing on the antioxidant level of tomatoes has previously been reviewed (Shi and Le Maguer, 2000), the exact level of losses or even gains of antioxidants have been reported to differ widely according to the type and conditions of the process applied and the variety/origin of the fruits used. Understanding the mechanisms taking place in the tissue during processing will lead to several innovations in the food industry required to control optimal technical and environmental parameters.

The demand for any kind of processing step usually stems from a variety of origins—the need to prolong shelf-life (e.g. fresh produce); to make products available out of season (e.g. tinned tomatoes); to produce products especially suited for home-consumption (e.g. tomato ketchup); to convert into new food products with alternative/supplemented flavor and texture (e.g. sauces, soups); to provide better nutritional characteristics; and, to add value for extra income. Processing strategies can range from being simple to being considerably complicated, depending on the end product. For example, fresh tomatoes require steps for washing, fruit selection, packaging, transporta-

**THERMAL TREATMENTS**

In most cases, the industrial processing of tomatoes into different end-products includes several temperature treatment steps such as drying, heating, pasteurizing, etc. These treatments have various goals—to inactivate microorganisms or enzymes, to decrease the moisture content and concentrate the product, or to soften the tissue in order to separate fruit from skin. During treatment, several additional changes can occur to affect the appearance, composition, nutritional value, and sensory properties in terms of color, texture, and flavor of the product. For example, frying, boiling, or microwaving has been shown to remove 35–78% of the quercetin conjugates that were originally present in the starting material (Crozier et al., 1997). These losses may be due to degradation, complex formation, or extraction of flavonols into the boiling water. In contrast, tomato juices and purées are generally rich sources of flavonols. Here, processing into the end product can increase the content of free quercetin by up to 30%, a change that may be brought about by enzymatic hydrolysis of quercetin conjugates. Tomato juice and puree have been shown to contain 15.2 to 16.9 mg/L and 16.6 to 72.2 mg/kg fresh weight of flavonols, respectively (Stewart et al., 2000). Fresh fruits collected from different regions were found to contain just 1.3 to 22.2 mg/kg fresh weight of flavonols (Stewart et al., 2000). On the other hand, canned tomatoes are known to be a poor source of flavonols (Shahidi and Naczk, 2004). Looking separately at the individual (groups of) components and following each processing step are both key to understanding the true nature of any changes observed. The effect of various thermal treatments on some of the key individual functional components is therefore reviewed separately.

**Lycopene and other Carotenoids**

All *trans* lycopene is the major pigment component in ripe red tomatoes and has often been studied in terms of its
Potential health benefits, bioavailability, and the changes that occur during fruit ripening and subsequent processing. Tomatoes and tomato products are the primary suppliers of lycopene to the human diet while other foods such as apricots, pink grapefruit, watermelon, guava, and papaya are also recognized as (seasonal) dietary sources (Russell, 2001). Besides lycopene, tomatoes also contain \( \alpha-, \beta-, \gamma-, \delta- \) carotene, and lutein and also neurosporene, phytene, and phytolfluoene (Riso and Porrini, 2001; Bino et al., 2005). Of all the carotenoid pigments, lycopene is not only the most abundant but also is the most efficient singlet oxygen quencher (free radical scavenger) with a capacity found to be more than twice that of \( \beta- \) carotene (Di Mascio et al., 1989). Lycopene in tomato seems also to be more stable to changes occurring during peeling and juicing than the other carotenoids. Among the commercial juices tested, tomato juice was found to have a higher oxygen radical absorbance capacity than both orange juice and apple juice. According to Anese et al. (1999), the antioxidant activity of tomato juice decreased after an initial 2–5 hours of heating but was restored after prolonged heating. Gazzani et al. (1998) reported that while boiled vegetable juices were generally found to express antioxidant activity, tomato juice was pro-oxidant. These contradictory findings may be explained by differences in the amounts of the antioxidant compounds in the tomato juices as Gazzani et al. (1998) used a filtration method which resulted in the loss of most of the juice coloration.

The effect of thermal treatments on lycopene in tomato products has attracted much attention (Sharma and Le Maguer, 1996; Zanoni et al., 1999; Shi and Le Maguer, 2000; Takeoka et al., 2001; Graziani et al., 2003; Sahlin et al., 2004; Goula and Adamopoulos, 2005; Goula et al., 2006; Toor and Savage, 2006). Lycopene appears to be a relatively stable compound during food processing but it has been reported that heating tomato pulp to produce paste, ketchup, juice and other products, can cause degradation of lycopene and other carotenoids (Sharma and Le Maguer, 1996). Heating tomato juice for 7 min. at 90°C and 100°C resulted in only small (1.1 and 1.7% respectively) decreases in lycopene content (Shi and Le Maguer, 2000). Drying tomato halves at 110°C for approximately 4 hours caused a lycopene loss of 12% (Zanoni et al., 1999). Also, semi-drying of fruit quarters at 42°C for 18 hours resulted in 10.5–20.5% loss of lycopene in three different tomato cultivars (Toor and Savage, 2006). In another study, a statistically significant loss in lycopene at levels of 12–28% was observed when tomatoes were processed into paste (Takeoka et al., 2001). According to this study, significant losses in lycopene occurred upon processing tomatoes into paste but overall losses were less than 30%—much lower when compared to losses observed when pure lycopene was used in model systems under similar conditions. In the study conducted by our group, the overall effect of processing from tomato to paste was a 32% decrease in lycopene content which was found to be statistically significant (Capanoglu et al., 2008).

Other antioxidants naturally present in tomato, such as vitamin C, vitamin E, polyphenolic flavonoids, and non-lycopene carotenoids, may play a role in preventing the degradation of lycopene (Takeoka et al., 2001; Sanchez-Moreno et al., 2006). Shi et al. (2004) evaluated the synergistic effect of lycopene with other tomato carotenoids. Tomato juice which was enriched in vitamin C (according to the label description) showed the highest lycopene content among the juices tested. However, possible interactions between antioxidants and other compounds in tomatoes have, to date, been insufficiently investigated (Riso and Porrini, 2001). Loss of antioxidants as a result of oxidative damage especially during drying has also been evaluated (Shi et al., 1999; Zanoni et al., 1999; Lavelli et al., 2000; Giovanelli et al., 2002; Goula et al., 2006). From these studies, it has been proposed that oxidative damage can be reduced by optimizing operating conditions for both drying and storage of dried tomato products. For example, low temperature application for short periods, reduction of flesh thickness, partial removal of water, or osmotic and vacuum drying techniques can be used to obtain dried tomatoes with higher antioxidant activities (Zanoni et al., 1999). Some of these techniques were within the scope of several researchers but more investigation is necessary (Lavelli et al., 1999; Shi et al., 1999; Toor and Savage, 2006).

It has been observed that there is an increase in the bioavailability of some carotenoids as a result of heating and cell wall disruption (Gartner et al., 1997; Russell, 2001). Böhmer and Bitsch (1999) provided evidence to support this view by demonstrating that intestinal absorption of lycopene from tomato juice (processed tomatoes) was better than from raw tomatoes. Recently, researchers reported that bioavailability, antioxidant activity, and other nutritional properties of tomato products may also be improved by heat treatment. A higher antioxidant activity was obtained through thermal treatments such as steaming, microwaving, frying, and drying of the tomato fruits (Chen et al., 2000; Chang et al., 2006). Graziani et al. (2003) showed that lycopene content significantly increased when tomatoes were heated in an oil bath at 100°C for 2 h. Re et al. (2002) also reported that processing tomato pulp under different temperatures for paste production resulted in higher lycopene content and a higher antioxidant activity. According to the results of Gahler et al. (2003), homogenization and thermal treatments during the production of tomato juice resulted in increases in both total hydrophilic and lipophilic antioxidant activities.

Shi and Le Maguer (2000) suggested that, during processing, heat induces isomerization of all \( trans \) to various \( cis \)-forms of lycopene, and Dewanto et al. (2002) found that the total \( trans \) and \( cis \)-lycopene content in the tomatoes increased with longer heating times. Abushita et al. (2000) also proposed that \( trans \) to \( cis \)-isomerization of \( \beta- \) carotene and lycopene occurred during thermal processing of tomato, particularly during the dehydration step in paste production. Besides isomerization reactions during thermal processing, increased carotenoid concentration is probably also due to greater extractability, enzymatic degradation, and possible unaccounted losses of moisture and soluble solids (Heinonen and Meyer, 2002).

Dewanto et al. (2002) and Chang et al. (2006) suggested that thermal processes might break down cell walls and weaken the
bonding forces between lycopene and the tissue matrix. Such disruptions in the cell wall fraction may enhance the release of phytochemicals from the matrix. This may make lycopene more accessible or more stable and thus increase the nutritional quality and antioxidant activity of product. On the other hand, Abushita et al. (2000) reported increases in total carotenoid and all trans-lycopene contents in the dry matter of tomato paste, of 29% and 37%, respectively. This was most likely due to the removal of seed and peel material and a loss of soluble volatile compounds during the evaporation steps. Seybold et al. (2004), observed an increase in the lycopene content of tomato sauce made from Spanish tomatoes whereas they have found a decrease in sauces prepared from Dutch tomatoes, suggesting cultivar-dependent effects. An increase in carotenoids by thermal processing has also been attributed to enzymatic degradation which causes weakening in protein-carotenoid aggregates (Sahlin et al., 2004).

In conclusion, the different behaviors of processed tomatoes which have been observed—both increased and decreased content of lycopene and/or other components is difficult to assess. Contrasting results may be due to differences in the type or variety of the tomatoes used, fruit ripeness, agricultural treatments, conditions such as temperature, time, presence of oxygen or light, and methods of processing, or it might simply be a matter of sub-optimal extraction of the compounds to be analyzed. It was also reported that even the extractability of carotenoids may vary according to the ripening stage, firmness, and genotype of the fruit (Seybold et al., 2004). Consequently, it is somewhat difficult to compare the data available on the antioxidant capacities of tomato and its products. A full, clear picture will only be obtained when proper fully-documented experiments are performed, where full histories of the materials used (from the variety and seed sowing all the way through to the conditions of product storage) are available for reference.

**Vitamin C and Tocopherols**

The vitamin C (ascorbic acid) content of fresh tomatoes depends on the variety and the cultivation conditions (Abushita, 2000). During processing, vitamin C is destroyed mainly due to oxidation reactions and the heat applied in the presence of air (Leoni, 2002). In addition to the effect of oxygen, such high temperature applications themselves cause oxidative stress. The decrease in vitamin C content of tomatoes following several heat applications and processes has been reported extensively in the literature (Zanoni et al., 1999; Giovanelly et al., 2002; Gahler et al., 2003; Sahlin et al., 2004; Capanoglu et al. 2008). The degree of loss of ascorbic acid is closely correlated to the drying temperature used for the production of the end product. For example, drying at 80 °C resulted in 10% residual ascorbic acid content whereas all the ascorbic acid was lost upon drying at 110 °C (Zanoni et al., 1999). Abushita et al. (2000) also reported that during hot-break extraction fruit material lost about 38% of its original ascorbic acid, and further processing to produce tomato paste by vacuum evaporation caused the product to lose an additional 16% of the ascorbic acid content. In this study, just 45% of the initial content of ascorbic acid was retained in the final tomato paste. Consequently, this level may play an additional, important role in protecting tomato paste from further oxidative degradation during storage or cooking (Abushita et al., 2000).

Vitamin E in tomatoes is predominantly represented by α-tocopherol. Like lycopene, vitamin E belongs to the lipophilic antioxidant fraction of the tomato fruit and has been linked to positive effects on human health. Investigations on the effects of tomato processing on the content of vitamin E are scarce. In a study conducted by Abushita et al. (2000), compared to values for the starting material, 20% of α-tocopherol was lost during thermal processing of tomato paste, while 47% α-tocopherol quinone and 33% γ-tocopherol were lost. According to Seybold et al. (2004), homogenization and sterilization of tomatoes during tomato juice production resulted in significant losses in α-tocopherol both on wet and dry weight bases. According to our results, the lipid-soluble antioxidants α-tocopherol and β-tocopherol were not affected by the industrial processing. On the other hand, their biosynthetic precursors, γ-tocopherol, and δ-tocopherol decreased by 84% and 69% respectively in the paste samples (Capanoglu et al., 2008). γ-Tocopherol was found to be highest in the jelly parenchyma tissue of the tomato fruit (Moco et al., 2007) and can easily be lost during processing steps which includes the removal of the seeds from the tomato fruit. Again, in full contrast, short-term heating of tomato sauce, tomato soup, and baked tomato slices led to a significant rise (51–73%) in α-tocopherol content on both wet and dry weight bases (Seybold et al., 2004).

**Total Phenolics, Flavonoids, and Hydrophilic Antioxidant Activity**

Similar to the findings for lycopene, in the current literature there are also conflicting results for total phenolics, flavonoids, and the total hydrophilic antioxidant activities of processed tomato samples.

Some studies indicate that a considerable loss of hydrophilic antioxidants is caused by the processing approach. For example, Crozier et al. (1997) studied the effect of cooking on the quercetin content of onions and tomatoes. With both vegetables, boiling reduced the quercetin content by 80%, microwave cooking by 65%, and frying by 30%. In contrast, the total phenolic content was found to be increased as a result of processing in other studies. In experiments conducted by Chang et al. (2006), two tomato varieties (Sheng-Neu (SN), and I-Tien-Hung (ITH)) were air dried (AD) at 80 °C for 2 hours and then at 60 °C for 6 hours. Subsequently, analyses revealed that the total flavonoid content in AD-SN was increased by 89% and in AD-ITH, by 50%. The total phenolic content increased by 13% and 50% respectively, when compared to the corresponding levels in fresh tomatoes (Chang et al., 2006). Similar to lycopene, the
The total phenolic and carotenoid contents of tomato have been observed to increase during processing (Dewanto et al., 2002). This increase of the hydrophilic antioxidant capacity was proposed to be primarily dependent on an increase in phenolic levels (Gahler et al., 2003).

At least a partial explanation in the apparently contradictory results on the effects of processing on tomato (total) antioxidant capacity may lie in the fact that differences may arise from multiple contrasting qualitative/quantitative changes taking place in the biochemical composition. Changes in the antioxidant activity of tomato products are complex both due to the broad range of biochemical components which are involved and also antioxidant activities can change depending on the individual components and on the treatments applied. Initial results suggest that while, for example, losses in antioxidant activity may be expected due to decreased lycopene content during processing, this may be (partially) compensated for by concomitant increases in the antioxidant activity of other components, and particularly, the hydrophilic polyphenolics. In other words, quantitative measurements of total antioxidant levels may not reflect significant qualitative/quantitative shifts of individual antioxidative components. For this reason, on-line antioxidant measurement approaches (Fig. 1) have been designed (Koleva et al., 2001, Beekwilder et al., 2005) and have already also been applied to tomato (Capanoglu et al., 2008). Further studies characterizing the specific changes in polyphenol content and antioxidant activity during thermal processing are still required before we can fully understand how the final biochemical composition of processed foods might subsequently be related, to the prevention of human diseases (Takeoka et al., 2001).

In view of the available literature, it is apparent that heat treatment may produce changes in the extractability of phenolics due to the disruption of the plant cell wall and thus result in an easier release of bound polyphenolic and flavonoid compounds (Peleg et al., 1991). Heat treatments can also deactivate endogenous oxidative enzymes. Therefore, another reason for the increased level of antioxidants was explained by the prevention of enzymatic oxidation reactions which cause losses of such compounds in the raw plant materials (Dewanto et al., 2002; Choi et al., 2006). Another reason for the increase in the hydrophilic antioxidant capacity is the formation of Maillard products. Maillard products are often antioxidant-active substances formed at high temperatures and have been suggested to balance the loss of vitamin C or even to lead to an increase in the hydrophilic antioxidant capacity (Gahler et al., 2003).

In other studies the total phenolic and carotenoid contents of tomato have been reported to be quite stable during processing under high temperature conditions. Thermal processing was shown to release more bound phenolics due to the breakdown of cellular constituents (Dewanto et al., 2002). This increase of the hydrophilic antioxidant capacity was proposed to be primarily dependent on an increase in phenolic levels (Gahler et al., 2003).

Industrialsystems

Graziani et al. (2003) applied heat treatments in samples produced under both laboratory and industrial scale conditions to observe changes in carotenoids and antioxidant activity. However, since the processing methods and conditions were different for industrial and lab-scale production, the results cannot be directly compared. Capanoglu et al. (2008), worked closely with a Turkish tomato paste factory and obtained samples from each step during the paste production process, from the tomatoes arriving at the factory gate to the final canned product (Fig. 2). Both targeted (e.g. for carotenoids) and untargeted (LC-MS of semi-polar, hydrophilic extracts) metabolomics approaches were used to follow biochemical changes after each step. Results showed that a multitude of modifications took place, involving both increases and decreases in individual components. Those steps causing the greatest changes were identified and predictions were made as to how these steps could be tackled in a modified processing strategy to improve the antioxidant capacity of the end product.

Abushita et al. (2000) also analyzed samples taken from three steps of paste processing (raw tomato, crushed sieved puree, and...
pasteurized paste) which were obtained from a canning factory in Hungary. The results showed that the contents of ascorbic acid and tocopherols decreased during processing while carotenoids either remained unchanged or were found to increase. During processing a conversion from trans to cis isomerization of β-carotene was observed. In another study, also using samples obtained from a commercial factory, Takeoka et al. (2001) observed statistically significant decreases (9–28%) in both lycopene and vitamin C as the tomatoes were processed into paste. Although both studies evaluated samples taken from a factory instead of lab-scale production, assessment of their findings is limited as not every step in the production process was followed and thus did not provide a full insight into when exactly, specific changes in antioxidants arose.

Figure 1  On line antioxidant detection in red (ripe) tomato fruits. Both hydrophilic (aqueous methanol) extracts and lipophilic (methanol-chloroform) extracts were prepared from tomato fruits and analyzed using HPLC-PDA with on-line antioxidant detection using C18-reversed phase and C30-reversed phase chromatography, respectively (Bino et al. 2005, Capanoglu et al. 2008). Upper traces show max plots of PDA detector (240-600nm); lower traces show antioxidant reactivity with ABTS• cation radicals at pH 7.4 (negative peaks). A: C18-HPLC of aqueous methanol extracts indicating main hydrophilic antioxidants; 1: vitamin C, 2: quercetin-3-O-rutinoside; 3: naringenin-chalcone. B: C30-HPLC of methanol–chloroform extracts indicating main lipophilic antioxidants; 4: naringenin-chalcone, 5: vitamin E; 6: all trans lycopene.
NON-THERMAL TREATMENTS

There is currently a general lack of information on the effect of non-thermal treatments on tomato products. Cutting, homogenization, peeling, etc., all potentially influence the antioxidant components. Lana et al. (2005) investigated the antioxidative capacity of fresh cut tomatoes and proposed that fresh cut tissues are primarily exposed to oxidative stress, presumably causing membrane damage and altering the composition and content of antioxidant compounds. Gahler et al. (2003) investigated home-preparation methods such as peeling, tomato soup preparation, etc., and three different steps of tomato juice production including sieving, homogenization, sterilization, filling, and pasteurization. Results suggested that homogenization increased the hydrophilic antioxidant capacity of the different tomato products. However, the exact mechanism still remains unclear. Similarly, in industrial processing, Capanoglu et al. (2008) also showed the “breaker” or homogenization step most significantly altered the biochemical composition as can be seen in Fig. 3 which shows the results of Principal Components Analysis (PCA) of untargeted metabolomics data obtained for the production steps of tomato paste. During direct consumption of tomatoes, consumers may prefer to remove some parts of the fruit such as skin, calyx, and/or seeds. However, it has been reported that tomato skin has significantly higher levels of (poly) phenolic antioxidants compared to the pulp (Muir et al., 2001; Toor and Savage, 2005). These findings were explained by suggesting that DNA-damaging UV light induces the accumulation of UV light-absorbing flavonoids and other phenolics, predominantly in the epidermal tissues of the plant (Toor et al., 2006). Of the total fruit flavonols, 98% was found in the tomato skin as conjugated forms of quercetin and kaempferol (Canene-Adams et al., 2004). The majority of studies investigating the antioxidant composition of different fractions of tomatoes just divided the tomato into skin and flesh portions while few studies investigated the seeds. In a recent detailed study, other parts of tomatoes including calyx, columella, and jelly parenchyma as well as epidermis and pericarp have been investigated with respect to their metabolite profile (Moco et al., 2007; Mounet et al., 2007). Tissues which are generally removed during tomato processing, such as calyx and skin, were found to contain high contents of carotenoids, flavonoids, and other compounds. For example, approximately one-third of the total weight of tomatoes in the form of skin and seeds is discarded during processing of tomatoes into paste (Al-Wandawi et al., 1985). Capanoglu et al. (2008) claimed that the losses in lycopene, β-carotene, and lutein of 4.6, 8.6, and 93.3%, respectively, were caused by this removal of seed and skin during the production. The additional loss is presumably attributable to oxidation reactions taking place during processing treatments (Capanoglu et al., 2008). Another observation from this study was the increase in rutin (the major quercetin-glycoside) and the total flavonoid content of the tomato material during the breaking step when the tomatoes are chopped into small pieces and subsequently homogenized. This increase has been proposed to result from the continuation of flavonoid synthesis as a response to wounding (Capanoglu et al., 2008). Similar observations have been reported for apples (Abdallah et al., 1997), lettuce leaves (Kang and Saltveit, 2002), and potatoes (Tudela et al., 2002). In contrast, Lana and Tjiskens (2006) found that freshly cut tomatoes had a lower antioxidant activity with respect to the intact fruit. However, they did observe an increase in the hydrophilic antioxidant activity later, at the end of the storage period, and reported that this might be due to some kind of repair or recycling mechanism.

METABOLICOMICS AS A NOVEL, MORE HOLISTIC ANALYTICAL APPROACH

The technology of metabolomics is developing into one with a wide range of fields of application (Hall, 2006). Using the latest Liquid Chromatograph (LC) and Gas Chromatography (GC) separation approaches together with Mass Spectrometry (MS), or Nuclear Magnetic Resonance (NMR) detection methods, so-called untargeted analyses (or fingerprints) are performed on plant extracts to give a very deep insight into the composition of these complex mixtures. Dedicated bioinformatics and bio-statistics software tools are then used to mine these complex datasets, which may contain information on as many as 1000 metabolites or more. Biochemical differences and differential metabolite markers for specific treatments, tissues, etc. can then readily be identified. Of importance in these analyses is that they are initially untargeted, meaning that previous knowledge on the biochemistry is not required and therefore will also not bias any choice of approach or the interpretation of the results obtained. Such analyses are already being applied in the field of food and nutrition (Hall, 2006; Hall et al., 2008) and metabolomics is providing valuable information on the composition of our food ingredients and how this is influenced by genetic and environmental factors.

Regarding tomato, metabolomics approaches have already been applied to generate very detailed information on genotypic (Schauer et al., 2008; Ursem et al., 2008) and tissue-specific

![Figure 2](image-url)
differences (Moco et al., 2007; Mounet et al., 2007) in tomato fruit. Capanoglu et al. (2008) have also already applied LC-MS-based metabolomics to follow the metabolic profiles of tomatoes throughout the industrial process leading to tomato paste. Through this approach, a wide range of different metabolic groups could be followed simultaneously and as a result, both qualitative and quantitative (positive and negative) differences were observed. Furthermore, specific differences could be associated with the different processing steps and hence a complete picture could be composed of how the end product is formed. Similar approaches are also being used to follow e.g. coffee processing (de Vos et al., 2007), tea (Del Rio et al., 2004), and rice (Fitzgerald et al., 2008). Many more similar applications are expected.

**SUMMARIZING INFORMATION LIMITATION AND DATA INCONSISTENCIES: RECOMMENDATIONS FOR FUTURE RESEARCH**

From the above review it is clear that there is a lot of interesting information out there, but that it is often difficult to interpret due to the different approaches, methods, materials, and analyses used. Below are given a number of recommendations as to how, in the future, we might approach this topic differently, in order to maximize the knowledge gained from this research.

- In the literature, there are many reports focusing on the effect of processing on the nutritional components of fruits and vegetables. In the case of tomatoes, those studies were mainly focused on compounds such as lycopene, β-carotene, and vitamin C or the total antioxidant potential of the processed tomato materials. There is, however, still limited information on the changes in the polyphenol/flavonoid content during processing of tomato (Toor and Savage, 2006; Chang et al., 2006; Gahler et al., 2003; Lenucci et al., 2006; Re et al., 2002). Considering the importance of this group of molecules, it is desirable to investigate the flavonoids, as well as related components in tomatoes in order to better understand the fate of all health-associated antioxidant compounds during processing.
- A reason for the present, apparently conflicting, results in the literature on the effect of processing is that most of these studies have employed laboratory-scale or pilot-scale
EFFECT OF INDUSTRIAL FOOD PROCESSING ON TOMATO ANTIOXIDANTS

The high antioxidant content in the waste products of tomato processing has been remarked by many researchers. However, possible recovery from these residues (such as seed and skin components) has been evaluated in only a limited number of studies. This waste deserves extra attention as it represents a potentially valuable source of functional ingredients for the food industry (Peschel et al., 2006) providing also high quality plant proteins (Sogi et al., 2005). In addition, processing waste may have a potential as raw material for producing alternative fuels (Giannelos et al., 2005).

The home situation: Having said all of the above, and having emphasized the need and desire for optimized processing strategies, there is still one aspect which can be of great relevance and that is what happens to processed products in the home after purchase. Most processed tomato products are usually cooked or at least heated up in some way before eating. Relatively little research has been done in this area and what happens in the home has been poorly characterized despite this step potentially undoing all the good work of the processors. Elucidating the extent of biochemical changes occurring during these secondary heat treatments is of critical importance and also deserves future attention.

CONCLUSIONS

The starting point for retaining the tomato’s excellent nutritional properties during processing into different products is the raw material. The quality of the fruit is therefore, a primary, key factor determining the (nutritional) quality of the end product. However, the processing of this material can be a major, usually negative, influence, especially where incorrect / sub-optimal procedures are applied. Hence, great attention should also be given to understanding and then avoiding or minimizing the detrimental effects of these technological processing methods. Here we have reviewed the effect of processing on the antioxidant level of tomatoes. The exact level of loss or even gain of antioxidants differs widely according to the type of treatment, the conditions of the process applied, and also the
variety/source/cultivation history of the fruits used. More precise research is required, covering information from the entire production chain, beginning with the variety of the seed planted, cultivation history, harvest time, etc. Understanding the mechanisms of biochemical change taking place in the tissue during processing is of primary importance. This is the first step which will lead to innovation in the food industry for controlling the technical and environmental parameters and hence, the optimization of the end product.

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