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Invited Review

The effect of food processing on bioavailability of tomato antioxidants

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Abstract. The role of antioxidants in human nutrition has gained increased interest, especially due to their associated health-beneficial effects for a number of chronic diseases, including certain types of cancer and cardiovascular disease. There is a particular interest in tomato as it is a major component in the so-called "Mediterranean diet" which has been associated with a healthier lifestyle. Tomatoes are rich sources of key antioxidant components such as carotenoids and polyphenols. They are consumed both as fresh produce and after having been processed in a wide variety of ways. Many researches have been carried out on the biochemical composition of tomato and its processed forms. However, in order to measure the real impact of tomato processing, bioavailability (the proportion of an ingested nutrient that is available for its intended mode of action) is more relevant than the total amount of antioxidants present in the original tomato or tomato product. Processing of tomatoes into different end products includes mechanical treatments, several thermal treatment steps, and the addition of ingredients such as oil or salt, which may result in changes in bioavailability of tomato antioxidants. In this review, we critically discussed the findings on the effects of different food processing techniques on *in vivo* and *in vitro* bioavailability of tomato antioxidants.

Keywords: Tomato, processing, bioavailability, antioxidant

1. Introduction

Tomato (*Solanum lycopersicum*) is one of the most popular and extensively consumed vegetable crops worldwide and a component of Mediterranean diet [1–4]. This fruit has been associated with the reduced risk of chronic degenerative diseases, such as cardiovascular diseases and certain types of cancer, especially prostate cancer [5, 6]. Moreover, consumption of tomato leads to decreased serum lipid levels and low-density lipoprotein oxidation [7, 8]. In a study that examined the relationship between the consumption of tomatoes and morbidity and mortality among 28,753 children aged 6–60 months, it was found that an intake of tomatoes for 2-3 days (compared with 0 days) was associated with a significant reduction in mortality (48%) and with a reduced risk of death associated with diarrhea [9]. Intake of tomatoes was also inversely associated with respiratory infections [10].

Epidemiological studies confirm that the observed health effects are due to the presence of different antioxidant molecules such as carotenoids, ascorbic acid, vitamin E and phenolic compounds [1, 11]. Table 1 contains the concentrations of the antioxidants present in tomato [12–15]. Among the carotenoids, mainly lycopene and β-carotene are of interest. Lycopene is the most abundant carotenoid present in tomatoes, accounting for more than 80% of the total tomato carotenoids in fully red-ripe tomatoes [16–18], and is responsible for the characteristic color

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Table 1
Antioxidants present in fresh red tomato fruit [12–15]

Compounds	Concentration (mg/kg)
Ascorbic acid	127
Carotenoids	
β-carotene	4
α-carotene	1
Lycopene	26
Lutein + zeaxanthin	1
Phytoene	19
Phytofluene	8
Flavonoids	
Quercetin glycosides	3–7
Kaempferol glycosides	2–8
Naringenin	8–42
Rutin	10–15
Phenolic acids	
Chlorogenic acid	13–38
Caffeic acid	29–56
p-Coumaric acid	16
Ferulic acid	7
Sinapic acid	2
Vanillic acid	1
Salicylic acid	1
Vitamin E	7

of tomatoes [19–21]. Moreover, lycopene is also the most efficient singlet oxygen quencher with a capacity found to be more than twice of β-carotene [22]. On the other hand, β-carotene is important due to its provitamin A activity [23]. Apart from carotenoids, tomato is also a source of ascorbic acid, which is an effective scavenger of superoxide, hydrogen peroxide, singlet oxygen and other free radicals [24]. The tocopherol content of tomato is also moderately high. Among the tocopherols, α-tocopherol is the most abundant form and exhibits the highest biological activity [25, 26].

Phenolic compounds are plant secondary metabolites, which are important determinants in sensory and nutritional quality of fruits and vegetables [27]. Many phenolic compounds exhibit antioxidative, anticarcinogenic, antimicrobial, antiallergic, antimutagenic, and anti-inflammatory activities [21]. The high content of phenolic compounds such as flavonoids and hydroxycinnamic acids in tomato has gained interest due to their apparent multiple biological effects, including free-radical scavenging, metal chelation, inhibition of cellular proliferation, and modulation of enzymatic activity and signal transduction pathways [3, 28]. However, the antioxidant contents of tomatoes depend on genetic (i.e., variety) and environmental factors (i.e., temperature, light, water and nutrient availability, etc.), the agricultural techniques used (i.e., use of plant growth regulators, date of harvest, etc.) and on the post-harvest processing and storage conditions [29–31].

Although tomatoes are commonly consumed as fresh, over 80% of the tomato consumption comes from processed products such as tomato juice, paste, puree, ketchup, and sauce [32–36]. Even though most of the nutritional components in tomato are stabilized by acidic pH of the fruit tissue and many of nutrients are conserved during relatively short and mild processing steps of tomato products, the antioxidant capacity of the products may change depending on processing type and conditions [2].

The effect of processing on the antioxidant level of tomatoes has previously been reviewed [2, 37]. Besides investigating the antioxidant capacity, it is also important to evaluate the bioavailability of health associated compounds present in tomato products, which will provide valuable data for elucidating the true biological relevance of these

compounds in the context of nutrition and human health. In this perspective, this review examines the findings reported on the effect of food processing on bioavailability of tomato antioxidants including carotenoids, especially lycopene and β-carotene and phenolic compounds.

2. Methods used to assess the bioavailability of antioxidants

Methods for determining bioavailability and/or bioaccessibility of antioxidants involve human (*in vivo*) or simulated experiments performed in a laboratory (*in vitro*). *In vivo* methods provide direct data of bioavailability and have been used for a great variety of nutrients [38]. Generally a response is measured after consumption of a pure nutrient either by humans or animals, and compared to an equivalent nutrient dose found in a food source [39]. Therefore, definitive conclusions on the bioavailability of a single phenolic compound are difficult to obtain, because of the synergistic effects of the mixture of polyphenols contained in each food matrix [40]. Mostly, *in vivo* bioavailability studies refer to the consumption of certain dose of a nutrient and following changes of its concentration in the blood plasma followed and compared with time. The main drawbacks of *in vivo* data are the variability in physiological state of individuals and the possible interaction of the nutrient with other components in the diet [41]. Moreover, such studies carried out in humans and/or animals are complicated, costly and raise ethical issues [42, 43].

In vitro methods for simulating the human digestive tract are being extensively used at present since they are rapid, safe, and do not have the same ethical restrictions as *in vivo* methods [44–46]. *In vitro* methods either simulate the digestion and absorption processes (bioavailability) or only the digestion process (bioaccessibility) and the response measured is the concentration of a nutrient in the final extract [47, 48]. The digestion process is simulated under controlled conditions using commercial digestive enzymes such as pepsin and pancreatin, while the final absorption process is commonly assessed using Caco-2 cell cultures [41, 49].

The methods that mimic the gastrointestinal (GI) digestion process under laboratory conditions are known as GI models. GI models reproduce the physiological conditions in the mouth, stomach, and small intestine during mastication, digestion, and absorption [38, 41]. These *in vitro* digestion methods have already been tested for foods such as orange juice [50], pomegranate juice [51], broccoli [52], raspberry [42], wine [43], chockberry [53], red cabbage [54], sweet cherry [55], grape [56], apple [57] and mulberry [46]. It has been proven that the measurement of bioavailability by *in vitro* GI models can be well correlated with conclusions from human studies and animal models [57]. Mahler et al. [58] reported that the estimation of iron bioavailability from the *in vitro* digestion/Caco-2 cell culture model has been well correlated, qualitatively, with human data.

Generally, GI models are divided into two broad categories: Static models, where the products of digestion stay generally immobile and physical processes such as shear, mixing and hydration are not simulated, and dynamic models which try to integrate physical and mechanical processes and temporal changes in luminal conditions to mimic parameters *in vivo* [38, 41]. In static *in vitro* digestion models, the stomach and the upper part of the small intestine are simulated by addition of salts and enzymes, adjustment of pH and incubation at 37°C. During the initial gastric phase, samples are incubated at gastric pH in the presence of gastric enzymes such as pepsin. The upper part of the small intestine, the duodenum, is then simulated by increasing the pH and addition of pancreatic enzymes and bile salts. Some models also contain an initial oral digestion phase, which mimics mastication in the presence of an enzyme amylase [59]. Moreover, there are also some models that include colon fermentation [60]. The dynamic *in vitro* digestion models, such as the TNO GI model (TIM) have the same basic principles, however they simulate better the conditions in the GI tract [61]. The TIM model contains four serial sections simulating the stomach, duodenum, jejunum and ileum [62–64]. Dynamic models have advantages over static models including continuous removal of nutrients, simulation of peristalsis and more controlled, gradual changes in pH and enzyme levels [65].

"Caco-2 cells" which are used in assessing the final absorption process, is the short name of polarized human colon carcinoma cells line [41, 66]. This model was originally performed to measure the bioavailability and toxicity of drugs; however, it is also used to study the uptake and transport of various antioxidants such as phenolic acids [67], flavanols [68, 69] anthocyanins [70, 71] and carotenoids [72–75]. The Caco-2 cells grow to form a monolayer, which then spontaneously differentiates to create many structural and functional components of intestinal cells. These components contain microvilli, tight junctions between the cells and "brush border enzymes", which means that the Caco-2 cell line can be used to study active and passive uptake and transport of nutrients. The major problem with the

Caco-2 cell line is that cellular uptake of nutrients varies between experiments depending on the general condition and passage number of the cells. Therefore, results can only be compared within the same experiments [65].

3. The effect of tomato processing on bioavailability/bioaccessibility of tomato antioxidants

Bioavailability is an important aspect when studying the role of antioxidants in human health. The interest in this aspect is increasing as food companies continuously involve in developing new products, defined as "functional" by the presence of specific antioxidants or phytochemicals [76].

The term "bioavailability" was originally used in pharmacology to define the "rate and extent to which a drug reaches its site of action" [77–80]. Although several other definitions of bioavailability have been stated, the most suitable one appears to be the fraction of an ingested nutrient or compound that reaches the systemic circulation and the specific sites where it can exert its biological action [76]. In other words, it shows how much of the ingested quantity of the nutrient is able to exert its beneficial effects in target tissues [40]. Another term that is commonly used is "bioaccessibility", which is defined as the amount of an ingested nutrient that is available for absorption in the gut after digestion [81–84]. When the amount of recovered nutrient after digestion is of concern then the term "bioaccessibility" is used. Bioavailability is generally measured using *in vivo* assays (*e.g*. blood plasma of humans), so factors such as the individual variability, physiological state, dose, and presence of other meal components play important roles [41, 85].

Bioavailability of antioxidants depends on many factors. In a critical appraisal [76], the main factors recognized as affecting antioxidant bioavailability in humans were discussed and gathered under four main categories: factors related to the antioxidant (chemical structure, molecular linkage, etc.), factors related to the food/preparation (matrix characteristics, processing, etc.), factors related to the host (enzyme activity, genetics, etc.) and external factors (food availability, different environmental factors such as sun, rain, etc.). The most important determinants of bioavailability are the chemical structure of the aglycone and the type of glycoside. The bioavailability of different glycosidic forms of the same aglycone varies [86].

Some specific classes of antioxidants including carotenoids and polyphenols, worth special consideration in case of tomatoes since they are well represented in this fruit and they can exert different functions having significant impact on human health. In this section, the effects of tomato processing on bioavailability/bioaccessibility of these compounds were examined.

3.1. Lycopene

Lycopene is a symmetrical, acyclic carotenoid with thirteen double bonds, eleven of which are conjugated. Because of its characteristic structure, lycopene is a powerful antioxidant [87, 88]. Each double bond of the lycopene polyene chain can exist in two configurations, giving rise to over a thousand possible isomers. However, only a limited number of cis-isomers occur in nature. These cis-isomers are interesting because they show higher antioxidant activity than all-trans-lycopene [89, 90]. Lycopene has to be absorbed into the blood stream and reach its site of action to perform its health effects. Therefore, lycopene content alone is not a complete indicator of nutritional value. As it is known, the nutritional value can be obtained by measuring the nutrient bioavailability [91]. Since lycopene is not synthesized in the human body, sufficient uptake from the diet is essential to benefit from its health promoting effects. The main sources of lycopene in the diet are tomatoes and tomato-based products [90]. Lycopene is present in the tomato chromoplasts where it occurs as carotenoid-protein complexes or as solid microcrystals [37]. Therefore, the release and subsequent absorption of lycopene from raw tomato is low [92]. The food matrix in which lycopene is coupled can be altered by food processing greatly affects the lycopene bioaccessibility [93, 94].

The effect of tomato processing on lycopene content is widely examined both in *in vivo* (Table 2) [95–99] and *in vitro* (Table 3) [90–93, 100–107] studies. Many studies demonstrated that processing operations, such as those involving heat treatment rupture the cell walls, favoring the release of lycopene from tomato chromoplasts and hence enhancing lycopene bioavailability/bioaccessibility [90, 92, 95–98, 100–104, 107]. However, controversial results regarding the impact of heat on lycopene bioavailability/bioaccessibility can also be found in literature. For instance, cooking of cherry tomatoes for 15 min at 100°C did not change the lycopene concentration in plasma [99]. Similarly,

Table 2
Processed tomato products subjected to *in vivo* bioavailability studies

Nutrient	Processing	Result	Reference
Chlorogenic acid	Cooking (15 min, 100°C)	Significant increase after 2 h ($p < 0.05$)	[99]
Lutein	Tomato vs. tomato puree	Decrease (∼65%)	[96]
	Tomato vs. tomato juice	NSD ($p < 0.05$)	[97]
Lycopene	Tomato vs. tomato paste	Significant increase (∼2.5 fold) ($p < 0.05$)	[95]
	Tomato vs. tomato puree	Increase (∼18%)	[96]
	Tomato vs. tomato juice	Significant increase (∼23%) ($p < 0.05$)	[97]
	Severe homogenization (blending for 2.5 min + HPH at 200 bar)	Significant increase ($p < 0.05$)	[98]
	Cooking (15 min, 100°C)	NSD ($p < 0.05$)	[99]
Naringenin	Cooking (15 min, 100°C)	Significant increase after 2 h ($p < 0.05$)	[99]
TAC	Tomato vs. tomato juice	NSD ($p < 0.05$)	[97]
	Severe homogenization (blending for 2.5 min + HPH at 200 bar)	Significant increase ($p < 0.05$)	[98]
Zeaxanthin	Tomato vs. tomato puree	Decrease (∼33%)	[96]
	Tomato vs. tomato juice	NSD ($p < 0.05$)	[97]
α-carotene	Tomato vs. tomato paste	NSD ($p < 0.05$)	[95]
	Tomato vs. tomato puree	Decrease (∼50%)	[96]
β-carotene	Tomato vs. tomato paste	NSD ($p < 0.05$)	[95]
	Tomato vs. tomato puree	Decrease (∼55%)	[96]
	Tomato vs. tomato juice	NSD ($p < 0.05$)	[97]
	Severe homogenization (blending for 2.5 min + HPH at 200 bar)	Significant increase ($p < 0.05$)	[98]
	Cooking (15 min, 100°C)	NSD ($p < 0.05$)	[99]
β-cryptoxanthin	Tomato vs. tomato puree	Decrease (∼44%)	[96]
	Tomato vs. tomato juice	NSD ($p < 0.05$)	[97]

TAC: Total antioxidant activity; HPH: High pressure homogenization; NSD: Not significantly different.

no effect of boiling, grilling, microwave-cooking, or steaming of quartered tomatoes was found on the lycopene bioaccessibility [102]. On the other hand, non-thermal processing seems to have an adverse effect on bioaccessibility of lycopene. For example, the loss of cell integrity observed with increasing ultrasonication time was accompanied by a decrease in lycopene bioaccessibility [91]. Colle et al. [94] subjected tomato pulp to high pressure homogenization (HPH) at pressures ranging from 0 to 1327 bar. Although HPH clearly disrupted the cellular structure of the tomato pulp, a decreasing trend of lycopene bioaccessibility with increasing pressure was observed. In the study of Svelander et al. [105], a heated 5% olive oil/tomato emulsion was homogenized at 100 and 1000 bar. No change in lycopene bioaccessibility was noticed after HPH. The presence of oil in high pressure homogenized tomato puree also did not further improve the *in vitro* lycopene bioaccessibility during subsequent thermal or high pressure processing [106].

3.2. β-Carotene

β-Carotene is present in lower quantities than lycopene in tomato, but possesses some health benefits not gained by lycopene, such as provitamin A activity. In addition, studies indicate a higher relative bioavailability of β-carotene compared with lycopene in the tomato matrix [92]. In general, *in vivo* human studies regarding the effect of tomato processing (Table 2) showed that thermal treatment either not significantly changed [95, 97, 99] or reduced [96] the β-carotene bioavailability. About one third of the tomato cell wall is comprised of pectin. Pectin has a large impact on textural properties of tomato products, but has been shown to reduce the bioavailability of several carotenoids, including lycopene and β-carotene [108–110]. Suggested mechanisms behind the reduced bioavailability include

Table 3
Processed tomato products subjected to *in vitro* bioaccessibility studies

Nutrient	Processing	Result	Reference
Lutein	Tomato vs. tomato sauce	Increase (∼10%)	[100]
	Boiling (10 min, 100°C)	NSD ($p < 0.01$)	[102]
	Grilling (10 min, 800 W)	NSD ($p < 0.01$)	
	Microwave-cooking (50 s, 800 W)	Significant decrease ($p < 0.01$)	
	Steaming (10 min)	Significant decrease ($p < 0.01$)	
Lycopene	Tomato vs. tomato sauce	Increase (∼16 fold)	[100]
	Canning (85°C −90°C, 5–20 min)	NSD ($p < 0.05$)	[101]
	Sun-drying (4–7 days, 27–28°C)	Significant increase ($p < 0.05$)	
	Boiling (10 min, 100°C)	NSD ($p < 0.01$)	[102]
	Grilling (10 min, 800 W)	NSD ($p < 0.01$)	
	Microwave-cooking (50 s, 800 W)	NSD ($p < 0.01$)	
	Steaming (10 min)	NSD ($p < 0.01$)	
	Crushing (15, 30, 120 s)	NSD ($p < 0.05$)	[103]
	Crushing (15, 30 sn) + Heating (8 min, 95°C)	NSD ($p < 0.05$)	
	Crushing (15, 30 sn) + Boiling (20 min, 100°C)	NSD ($p < 0.05$)	
	Crushing (120 sn) + Heating (8 min, 95°C)	Significant increase ($p < 0.05$)	
	Crushing (120 sn) + Boiling (20 min, 100°C)	Significant increase ($p < 0.05$)	
	HPH (0–1327 bar)	Significant decrease at 0–479 bar	[94]
		NSD at 479–1327 bar	
	HPH + Thermal processing	Significant decrease at 0–479 bar	
		NSD at 479–1327 bar	
	Thermal processing (60–140°C)	NSD at 60–120°C ($p < 0.05$)	[90]
		Significant increase at 130°C and 140°C (∼2-fold) ($p < 0.05$)	
	Crushing (120 s) + Boiling (10 min, 100°C)	NSD ($p < 0.05$)	[92]
	Crushing (120 s) + LTLT (40 min, 60°C) + Boiling (10 min, 100°C)	Significant increase ($p < 0.05$)	
	Cutting + LTLT (40 min, 60°C) + Crushing (120 s) + Boiling (10 min, 100°C)	NSD ($p < 0.05$)	
	Crushing with 0.5% $CaCl_2$ (120 s) + LTLT (40 min, 60°C) + Boiling (10 min, 100°C)	NSD ($p < 0.05$)	
	Cutting + LTLT (40 min, 60°C) + Crushing with 0.5% $CaCl_2$ (120 s) + Boiling (10 min, 100°C)	NSD ($p < 0.05$)	
	Crushing (120 s) + HTST (4 min, 90°C) + Boiling (10 min, 100°C)	NSD ($p < 0.05$)	
	Cutting + HTST (4 min, 90°C) + Crushing with 0.5% $CaCl_2$ (120 s) + Boiling (10 min, 100°C)	NSD ($p < 0.05$)	
	Crushing (180 s) + Boiling (20 min, 100°C)	NSD ($p < 0.05$)	
	Crushing (180 s) + LTLT (40 min, 60°C)	Significant increase ($p < 0.05$)	
	Crushing (180 s) + LTLT (40 min, 60°C) + Boiling (20 min, 100°C)	Significant increase ($p < 0.05$)	
	Crushing (180 s) + HTST (10 min, 90°C)	Significant increase ($p < 0.05$)	
	Crushing (180 s) + HTST (10 min, 90°C) + Boiling (20 min, 100°C)	Significant increase ($p < 0.05$)	
	HPP (700 MPa, 30°C, 5 min)	NSD ($p < 0.05$)	[104]
	Preheating (0.1 MPa, 65°C, 5 min)	Significant decrease (∼10%) ($p < 0.05$)	

Table 3
(*Continued*)

Nutrient	Processing	Result	Reference
Lycopene	PATP (700 MPa, 100°C, 5 min)	NSD ($p < 0.05$)	[104]
	Thermal processing (0.1 MPa, 100°C, 5 min)	NSD ($p < 0.05$)	
	Hot break (93°C, 60 s) + HPP (700 MPa, 30°C, 5 min)	Significant increase (∼14%) ($p < 0.05$)	
	Hot break (93°C, 60 s) + Preheating (0.1 MPa, 65°C, 5 min)	Significant increase (∼16%) ($p < 0.05$)	
	Hot break (93°C, 60 s) + PATP (700 MPa, 100°C, 5 min)	Significant increase (∼11%) ($p < 0.05$)	
	Hot break (93°C, 60 s) + Thermal processing (0.1 MPa, 100°C, 5 min)	Significant increase (∼22%) ($p < 0.05$)	
	Heating with 5% olive oil + HPH	NSD ($p < 0.05$)	[105]
	Mild pasteurization (15 min, 450 MPa, 20°C)	NSD ($p < 0.05$)	[106]
	Intense pasteurization (20 min, 600 MPa, 45°C)	NSD ($p < 0.05$)	
	Sterilization (117°C, 1.5 min, 3 min)	Significant decrese ($p < 0.05$)	
	Ultrasonication (60 min, 24 kHz, 100 μm)	Significant decrease (∼50%) ($p < 0.05$)	[91]
	HPH (100 bar)	NSD at 100 bar ($p < 0.05$)	[107]
	Microwave heating (20 min, 70°C, 90°C, 120°C)	NSD at 70°C and 90°C ($p < 0.05$) Significant increase at 120°C ($p < 0.05$)	
	HPH + Microwave heating	NSD at 70°C and 90°C ($p < 0.05$) Significant increase at 120°C ($p < 0.05$)	[107]
TAC	Canning (85°C −90°C, 5–20 min)	Significant decrease (∼40%) ($p < 0.05$)	[101]
	Sun-drying (4–7 days, 27–28°C)	Significant decrease (∼23%) ($p < 0.05$)	
β-carotene	Tomato vs. tomato sauce	Increase (∼60 fold)	[100]
	Boiling (10 min, 100°C)	Significant increase ($p < 0.01$)	[102]
	Grilling (10 min, 800 W)	Significant increase ($p < 0.01$)	
	Microwave-cooking (50 s, 800 W)	Significant increase ($p < 0.05$)	
	Steaming (10 min)	NSD ($p < 0.01$)	
	Crushing (120 s) + Boiling (10 min, 100°C)	NSD ($p < 0.05$)	[92]
	Crushing (120 s) + LTLT (40 min, 60°C) + Boiling (10 min, 100°C)	Significant increase ($p < 0.05$)	
	Cutting + LTLT (40 min, 60°C) + Crushing (120 s) + Boiling (10 min, 100°C)	NSD ($p < 0.05$)	
	Crushing with 0.5% $CaCl_2$ (120 s) + LTLT (40 min, 60°C) + Boiling (10 min, 100°C)	NSD ($p < 0.05$)	
	Cutting + LTLT (40 min, 60°C) + Crushing with 0.5% $CaCl_2$ (120 s) + Boiling (10 min, 100°C)	NSD ($p < 0.05$)	
	Crushing (120 s) + HTST (4 min, 90°C) + Boiling (10 min, 100°C)	NSD ($p < 0.05$)	
	Cutting + HTST (4 min, 90°C) + Crushing with 0.5% $CaCl_2$ (120 s) + Boiling (10 min, 100°C)	NSD ($p < 0.05$)	
	Crushing (180 s) + Boiling (20 min, 100°C)	Significant increase ($p < 0.05$)	
	Crushing (180 s) + LTLT (40 min, 60°C)	NSD ($p < 0.05$)	
	Crushing (180 s) + LTLT (40 min, 60°C) + Boiling (20 min, 100°C)	Significant increase ($p < 0.05$)	
	Crushing (180 s) + HTST (10 min, 90°C)	Significant increase ($p < 0.05$)	
	Crushing (180 s) + HTST (10 min, 90°C) + Boiling (20 min, 100°C)	Significant increase ($p < 0.05$)	

Table 3
(*Continued*)

Nutrient	Processing	Result	Reference
β-carotene	HPP (700 MPa, 30°C, 5 min)	Significant increase (∼19%) ($p < 0.05$)	[104]
	Preheating (0.1 MPa, 65°C, 5 min)	NSD ($p < 0.05$)	
	PATP (700 MPa, 100°C, 5 min)	Significant increase (∼23%) ($p < 0.05$)	
	Thermal processing (0.1 MPa, 100°C, 5 min)	Significant increase (∼35%) ($p < 0.05$)	
	Hot break (93°C, 60 s) + HPP (700 MPa, 30°C, 5 min)	Significant increase (∼4%) ($p < 0.05$)	
	Hot break (93°C, 60 s) + Preheating (0.1 MPa, 65°C, 5 min)	Significant decrease (∼6%) ($p < 0.05$)	
	Hot break (93°C, 60 s) + PATP (700 MPa, 100°C, 5 min)	NSD ($p < 0.05$)	
	Hot break (93°C, 60 s) + Thermal processing (0.1 MPa, 100°C, 5 min)	Significant increase (∼6%) ($p < 0.05$)	
β-cryptoxanthin	Boiling (10 min, 100°C)	NSD ($p < 0.01$)	[102]
	Grilling (10 min, 800 W)	Significant decrease ($p < 0.01$)	
	Microwave-cooking (50 s, 800 W)	Significant decrease ($p < 0.01$)	
	Steaming (10 min)	NSD ($p < 0.01$)	

TAC: Total antioxidant activity; HPH: High pressure homogenization; LTLT: Low temperature long time; HTST: High temperature short time; HPP: High pressure processing; PATP: Pressure assisted thermal processing; NSD: Not significantly different.

an increased viscosity in the GI tract, leading to decreased carotene migration, inhibiting the micelle formation by binding of bile acids and phospholipids, as well as impaired activity of pancreatic enzymes [92].

The data in the literature concerning the absorption of β-carotene from processed tomato products is highly variable. In contrast with *in vivo* studies (Table 2), *in vitro* research on processed tomatoes (Table 3) showed that absorption of lycopene is enhanced as a result of thermal processing [92, 100, 102]. Moreover, non-thermal treatments such as high pressure processing also improved absorption of β-carotene [104]. More literature data on the effect of thermal processing on β-carotene *in vitro* bioaccessibility in carrots are available [111–114] and these studies support that thermal processing can enhance carotenoid *in vitro* bioaccessibility [90].

3.3. Other carotenoids

Besides lycopene and β-carotene, tomato and tomato products are also rich in other carotenoids including lutein, zeaxanthin, α-carotene and β-cryptoxanthin. Studies regarding the absorption of these carotenoids from tomatoes mainly focused on the effect of heat treatment (Table 2, 3). In fact, there are no studies examining the impact of non-thermal processing on bioavailability of these compounds. The findings on the influence of thermal processing on bioavailability/bioaccessibility are often contrasting, *e.g.* thermal processing increased [100], decreased [96, 102] or did not affect [97, 102] the lutein bioavailability. Similarly, thermal treatment of tomato and tomato products either decreased or did not modify the zeaxanthin, α-carotene and β-cryptoxanthin absoption [95–97, 102].

3.4. Phenolic compounds and antioxidant activity

There is limited information on the changes in bioavailability of polyphenols during processing of tomatoes (Tables 2, 3). In the study of Bugianesi et al. [99], cooking of cherry tomatoes at 100°C for 15 min significantly increased the plasma concentrations of naringenin and chlorogenic acid. Although there are some studies investigating the bioavailability of tomato and tomato products, studies on the effect of tomato processing on antioxidant activity are also scarce. Wooton-Beard et al. [115] evaluated the stability of commercial tomato juice antioxidants following *in vitro* digestion. The tested juices were either stable or enhanced in terms of total antioxidant capacity following *in vitro* digestion. In another study that investigated the tomato juice containing rutin, 86% of the ingested flavonol

disaccharide was recovered in ileal fluid collected over a 24-h period after ingestion [116]. Antioxidant capacity of human plasma was not altered significantly when fresh and cooked tomatoes were compared [97]. Homogenization significantly improved the antioxidant activity in plasma, whereas the effect of additional heat treatment was not significant [98]. Moreover, antioxidant activity of dialyzed fraction in the small intestine was significantly lower in canned and sun-dried tomatoes compared to fresh tomatoes [101].

4. Conclusion

This review investigated the findings reported on the effect of food processing on bioavailability of tomato antioxidants. The present findings are often conflicting, which might 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. Another reason associated to the employment of laboratory-scale or pilot-scale experiments. Simulation of tomato processing under laboratory conditions appears to produce significant deviations compared to the final products obtained from industrial scale process. In some studies, fresh and processed tomato samples were obtained from the local markets and information on their history (age, source, treatment, variety etc.) is unknown. However, it is well known that such factors are also important while determining the antioxidant content. In addition, variations in analytical techniques complicate the comparisons between different studies. There is limited or no information on the changes in bioavailability of polyphenols, ascorbic acid and vitamin E during processing of tomatoes. Therefore, future studies are recommended to be performed accordingly.

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