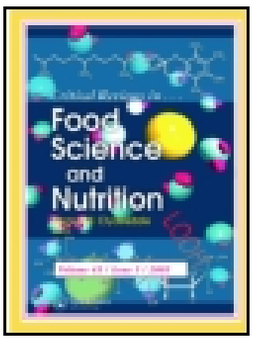

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Flavonoids in fruits and vegetables after thermal and nonthermal processing: A review

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ABSTRACT

Consumers currently demand more nutritious food, which is minimally processed and naturally produced. Flavonoids are one of the major plant metabolites found throughout the plant kingdom, especially in fruits and vegetables. Flavonoids exert tremendous positive effects on health and protect against various diseases. Fruits and vegetables are difficult to store for a long period, owing to their perishable nature even at low temperatures. Therefore, processing is necessary to prolong their shelf lives and increase nutritional values. Thermal processing has been used in the food sector since ancient times. However, nonthermal processing has become more attractive to consumers and product developers recently, owing to the retention of beneficial health properties after nonthermal processing. The present review will address the effects of thermal and nonthermal processing methods such as blanching, drying, high-pressure processing, ultrasound, pulsed electric field, and ultraviolet irradiation on total and individual flavonoid content in fruits and vegetables. In addition, this text will elucidate the stability characteristics as well as bioavailability, cytotoxicity, and transformations of flavonoids during thermal and nonthermal treatments.

KEYWORDS

Fruits; vegetables; flavonoids; thermal treatment; nonthermal

Introduction

In recent years, consumption of secondary plant metabolites has increased tremendously because of their numerous health benefits and because these compounds can also be used as functional compounds and natural food ingredients. Among several secondary plant metabolites, flavonoids are among the major plant metabolites found throughout the plant kingdom (Crozier et al., 2008). Vegetables, fruits, oilseeds, medicinal plants, and herbs are the major sources of flavonoids. It is very difficult to store fruits and vegetables for a long period because of their perishable nature, even at low temperatures. Therefore, processing is necessary to prolong their shelf life. Blanching, pasteurization, sterilization, and thermal drying such as sun drying, cross-flow, fluidized bed, osmotic air drying, and oven drying as well as drum, spray, puff, freeze, and microwave drying are commonly used for thermal processing in the food sector (Rawson et al., 2011). However, thermal processing has some detrimental effects on secondary metabolites. In this regard, consumers are also more conscious about their health and want to eat more nutritious food that is minimally processed and naturally produced (Tiwari et al., 2009). As a consequence, nonthermal methods such as high-pressure processing, pulsed electric field, ultrasound, irradiation, dense phase carbon dioxide, and ozone are gaining more popularity among the consumers because these approaches allow retention of the nutritional value in various functional foods. Sing et al. (2015) revealed a differential pattern of changes in the phytochemical matrix and anti-nutrients in vegetables after microwave boiling. Cooking had both positive and negative effects on the phytochemicals and antioxidant activities in the vegetables (Saikia and Mahanta, 2013). Pulsed electric field-treated samples of orange juice had more stable flavonoids and phenolic acids than those treated with thermal pasteurization (Agcam et al., 2014). Ultrasound-assisted extraction increases the bioactive compounds in the fruit peel (Prakash Maran et al., 2013).

Some reviews deal with effects of nonthermal processing technologies on the anthocyanin content of fruit juices (Tiwari et al., 2009) and the effect of thermal and non thermal processing technologies on the bioactive content of exotic fruits and the derivative products (Rawson et al., 2011), and effects of cooking techniques on vegetable pigments such as carotenoid and anthocyanin levels (Murador et al., 2014). Nayak et al. (2015) provided extensive data on the effects of processing on phenolic antioxidants of fruits, vegetables, and grains. Ioannou et al. (2012) demonstrated thermal effects on flavonols and anthocyanin and studied the degradation kinetics in some fruits and vegetables. It has already been proven that processing treatments can affect secondary metabolities either positively or negatively. However, there is no information about specific flavonoid content for selection of processing techniques, especially for fruits and vegetables. Based on the aforementioned information, therefore, the objective of this review was to illustrate the effect of thermal and non thermal techniques on flavonoids in different food sources. In addition, this review

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describes the stability and changes in the pathway of flavonoids during processing.

Classification and structure of flavonoids

Plant secondary metabolities are mainly subdivided into three groups based on their biosynthetic origin (Crozier et al., 2008): (i) flavonoids and related phenolic and polyphenolic compounds, (ii) terpenoids, (iii) nitrogen-containing alkaloids and sulfur-containing compounds. Flavonoids consist of 15 carbons along with two aromatic rings and the associated carbon bridge (Crozier et al., 2008). Classification, basic information, and some examples of flavonoids with their structure are shown in Figs. 1–3, respectively.

Mechanisms of action of flavonoids

It is well known that flavonoids serve as potent antioxidants. Reactive oxygen species and free radicals are responsible for many human diseases. Flavonoids can inhibit the production of reactive oxygen species and free radicals in the human body. Some flavonoids also work as antibacterial agents, and others have an antifungal activity. Quercetin, rutin, apigenin, catechin, and hesperidine have antiviral activity. Flavonoids also have anti-osteoporotic effects, antitumor effects, anti-inflammatory effects, and so on (Nijveldt et al., 2001). Mechanisms of action of flavonoids and their effects on diseases are shown in Fig. 4.

Thermal processing

Various thermal processing methods have been used in the food industry since ancient times. Thermal processing not only ensures microbiological safety but also preserves the nutritional value of food products. Kumar et al. (2014) revealed that to apply various thermal processing methods to food, several factors must be considered, such as (i) the type and heat resistance of the target microorganism, spore, or enzyme present in the food, (ii) pH of the food, (iii) heating conditions, (iv) thermo physical properties of the food and shape and size of the container, and (v) storage conditions. Tables 1 and 2 cover the effects of thermal processing on flavonoid content of fruits and vegetables.

The effect of thermal processing on flavonoid content of fruits

Water blanching (e.g., 75–95°C for 1–10 min) is more often used in the food industry owing to lower costs than with other blanching methods (Rawson et al., 2011). Generally, blanching is employed prior to further processing to inactivate enzymes. Blanched litchi juice has higher (−)-epicatechin, rutin, and total flavonoid contents than thermally processed (HT and UHT) litchi juice because enzyme is not inactivated by thermal treatment, and residual enzymatic activity contributes to reduced concentrations of (−)-epicatechin, rutin, and total flavonoids (Liu et al., 2015). Thermal stability (80°C for 1 to 60 min) of flavonoids in açai was evaluated by Pacheco-Palencia et al. (2009); they showed that flavone glycosides and flavonol derivatives remained unchanged during heating for up to 60 min. Blanching treatment had higher total flavonoid content in mango and ber fruits because blanching is capable of releasing phenolic phytochemicals from internal cells (Nohemi et al., 2012; Kavitha and Kuna, 2014), whereas ber fruit beverage

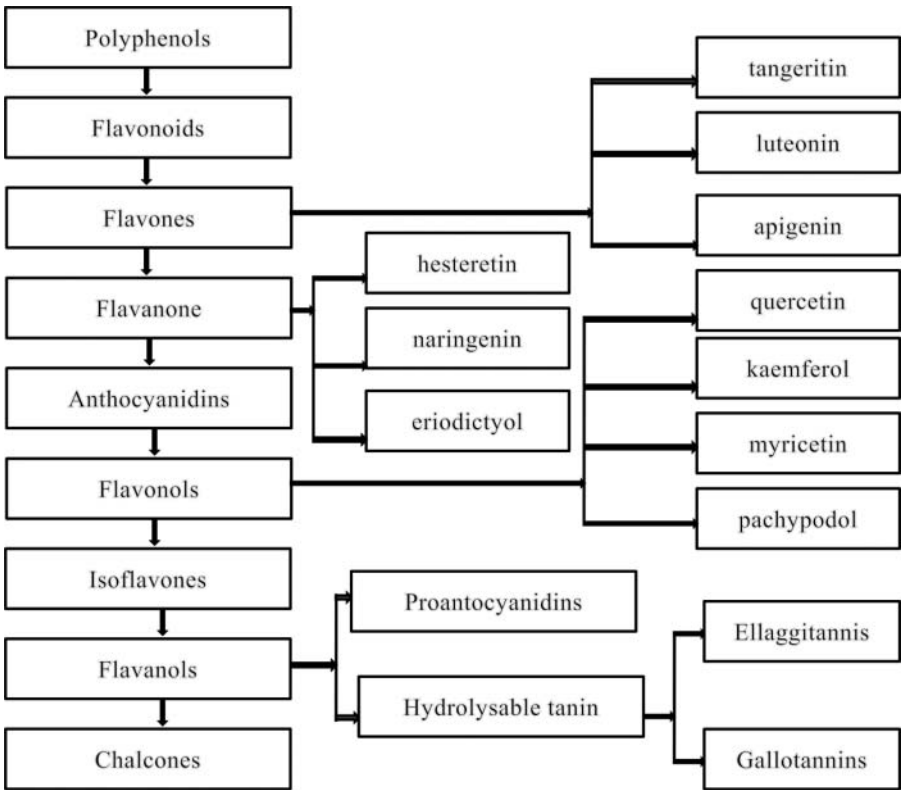

Figure 1. Classification of flavonoids (adapted from Ghasemzadeh and Ghasemzadeh, 2011; Albuquerque et al., 2013; Nayak et al., 2015).

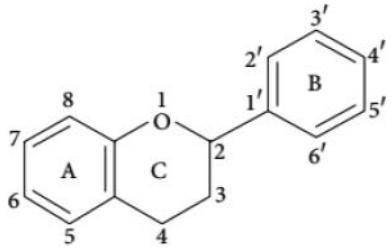

Figure 2. Basic flavonoid structure (adapted from Kumar and Pandey, 2013).

showed lower total flavonoid content as compared to raw ber fruit as mentioned in the same study. Cabrera and Moon (2015) found that 1 min of blanching yielded more flavonoid content in whole Campbell grapes before juice processing than did 5 min of blanching because of leaching out of some flavonoids. Blanched and unblanched samples retained the same flavonoid content in apple pomace before drying (Heras-Ramírez et al., 2012). However, fresh and thermally treated samples (90°C for 30 and 60 s) showed no significant difference in flavonoid content (kaempferol, quercetin, and myricetin) in strawberry juice (Odriozola-Serrano et al., 2008) and catechin content in grape juice (Marsellés-Fontanet et al., 2013), but thermal treatment (90°C for 30 and 60 s) produced lower content of kaempferol and quercetin in tomato juice, and thermal treatment (97°C for 15 min) yielded higher total flavonoid content in pineapple juice as compared to fresh juice (Odriozola-Serrano et al., 2009; Goh et al., 2012). Moreover, He et al. (2016) showed that thermal treatment (heating at 80°C for 30 min) markedly increased individual flavonoid content (naringin, hesperetin-rutinoside, naringenin-trisaccharide, luteolin-rutinoside, quercetin-trisaccharide, hesperidin, phloridzin, epigallocatechin gallate, and proanthocyanidin) in orange, apple, and grape juice, but elevated temperature (heating at 90°C for 30 s) produced a lower concentration of epicatechin and phloridzin than a control did. They found that more cells were disrupted after thermal treatment and the bound flavonoid content was increased, whereas degradation of epicatechin and phloridzin was probably related to oxidative degradation or polymerization. Another study revealed that thermal treatment (heating at 70°C for 30 s) yielded lower naringenin and hesperetin concentrations relative to untreated samples of orange juice during 40 days of storage at 4°C (Plaza et al., 2011). Thermal treatment (heating at 90°C for 90 s) showed a reduction trend in proanthocyanidin content in cranberry juice in comparison with control during storage (Giacarini, 2008). The degradation could be related to polyphenol oxidase and peroxidase. Low (35°C, 30 min) and high (70°C for 30 s) temperature treated orange juice had higher hesperetin concentration, but lower naringenin content (Sanchen-moreno et al., 2005). Pasteurization (90°C for 1 min) also induces increased concentrations of hesperidin, rutin, nariutin, and quercetin in a fruit juice-milk beverage (Morales-delapena et al., 2016) and also increases in hesperidin, rutin, narirutin, quercetin, and apigenin content in fruit juice-soya milk (Morales-delaPeña et al., 2011) relative to untreated samples. Both research groups also revealed that individual flavonoid content was not detected in an untreated sample after 21 days of storage. Another study revealed that total aglycone content significantly increased whereas no significant difference were found in total glucoside content in a fruit juice-soymilk beverage in a comparison between pasteurization (90°C for 60 s) and control samples after immediate processing. This effect might be due to hydrolysis of the malonyl forms under the effect of heat treatment (Morales-delaPeña et al., 2010). This research group also mentioned that the pasteurization sample had higher total isoflavone content than did control during storage. However, hesperidin concentration was higher and narirutin, eriocitrin, eriodictyol, naringenin, hesperetin, and kaempferol concentrations were lower in orange juice after thermal treatment (90°C/1 min) relative to fresh juice (Estrada, 2011). Usually, at lower pH, flavanones are precipitated thus leading to increased

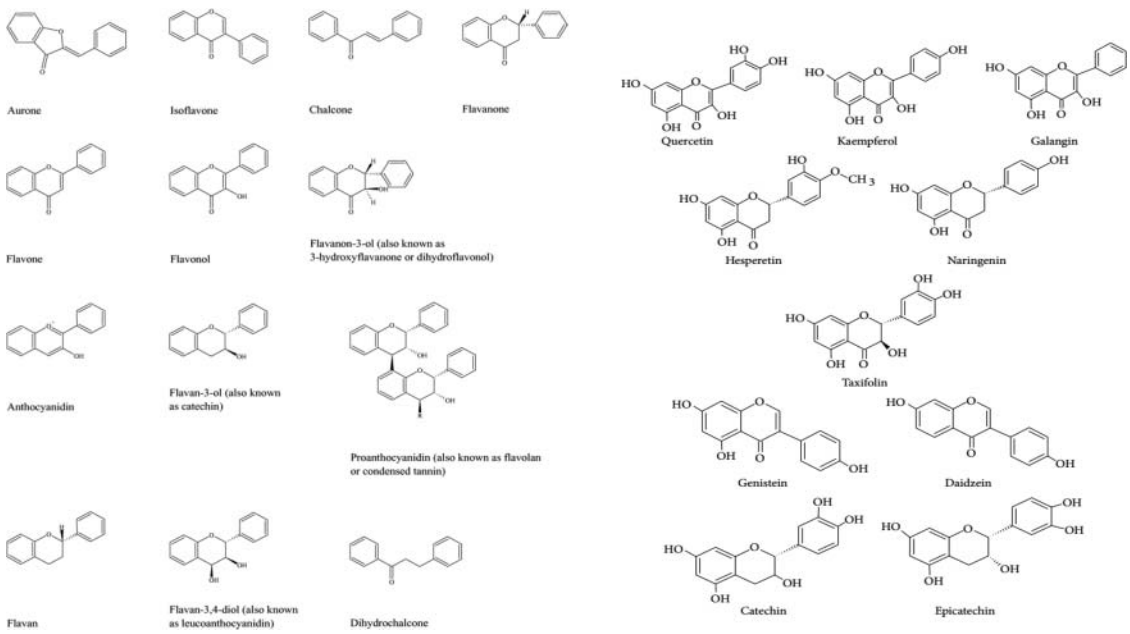

Figure 3. The backbone structures of the main classes of flavonoids (adapted from Cushnie and Lamb, 2005).

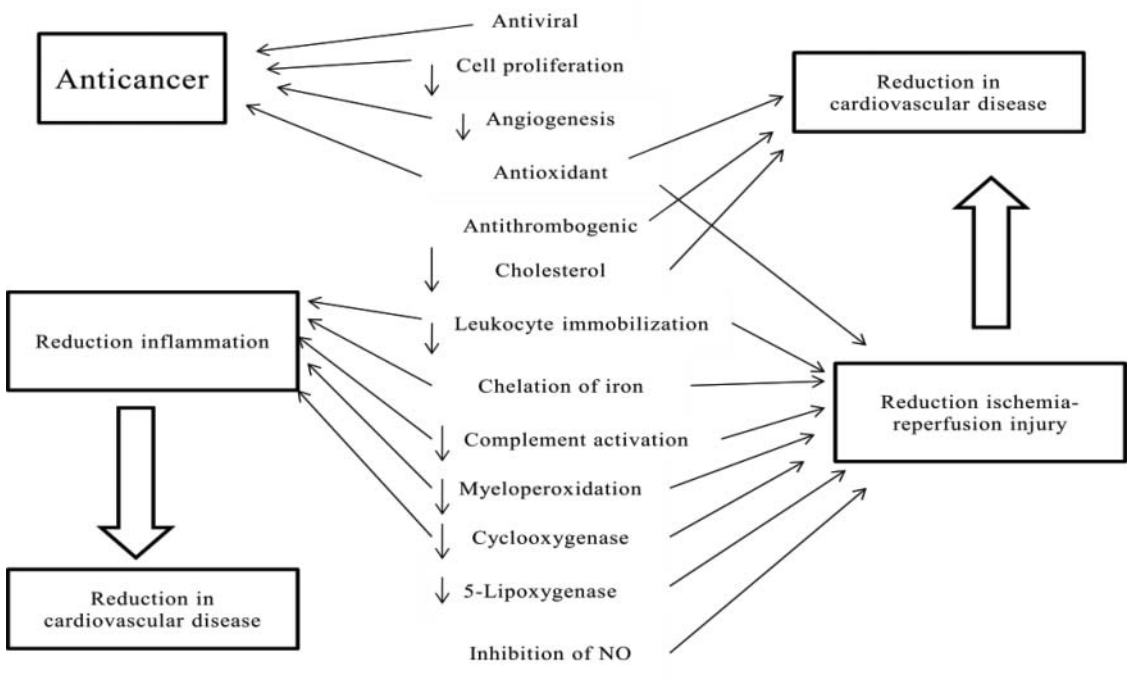

Figure 4. Mechanisms of action of flavonoids and their effects on diseases, with participation of NO, nitrous oxide (adapted from Nijveldt et al., 2001).

hesperetin content in orange juice. However, heat sterilization (131°C for 2 s) causes a loss of quercetin, kaempferol, and isorhamnetin in prickly pear juice as compared to fresh juice (Jiménez-Aguilar et al., 2015). Contradictory results were obtained by Davidov-Pardo et al. (2011) for grape seed who mentioned that sterilization could markedly enhance the concentrations of various flavonoids, followed by baking and cooking (in terms of the effect size). Greater flavonoid content might be released by ruptured cells; this phenomenon is more likely during sterilization. Blanching with hot water retains significantly higher tannin content than blanching with potassium meta bisulphate in experiments with Aonla shreds (Prajapati et al., 2011); it is possible that more tannin was lost after hot water blanching. However, blanching reduces tannin content in mandarin peel as reported by Ojha et al. (2016). Hoffmann-Ribani et al. (2009) reported that myricetin, quercetin, and kaempferol levels are higher in pasteurized frozen pitanga pulp than in fresh pitanga fruit because of degradation of flavonoid content during the thermal treatment. Pasteurization also increases the concentration of catechins and procyanidins in cold-pressed grape juices, but it decreases these concentrations in hot-pressed grape juices as revealed by Fuleki and Ricardo-da-Silva (2003). An increasing and decreasing tendency was observed for total flavonoid content in grape peels and plum peel, respectively, after pasteurization (70°C for 1 h) (Medina-Meza and Barbosa-Cánovas, 2015). Naringin, neohesperidin, hesperidin, kamferol, luteolin, and apigenin content in orange juice are increased whereas rutin, isoquercetin, quercetin, neoeriocitrin, eriocitrin, and naringenin content are decreased in pasteurized treated samples relative to control. However, kaempferol, luteolin, apigenin, and neoeriocitrin content are markedly increased, and the rest of flavonoid content is decreased at the end of storage (Agcam et al., 2014). Higher pasteurization temperature (75 ± 1°C for 20 s) yields greater amounts of tannin, catechin, gallocatechin, epicatechin, epicatechingallate, epigallocatechingallate, epigallocatechin, and procyanidins in grape seed as compared to lower pasteurization temperature (65 ± 2°C for 30 min) (Davidov-Pardo et al., 2011). Some researchers found a reduction in total flavonoid and quercetin aglycone content in mulberry juice during pasteurization (Yu et al., 2014; Wang et al., 2016). Santhirasegaram et al. (2015) showed a 25% reduction in total flavonoid content in mango juice after pasteurization (90°C for 6 s). Lower temperature (4°C) produced minor changes in flavonoid content of pasteurized pulp and acai juice as compared to a higher temperature (30°C) at the end of 30 days owing to polymerization reactions (Pacheco-Palencia et al., 2007). Usually, various types of reactions such as thermal degradation, depolymerization, and polymerization are the main reason for the degradation of flavonoids during pasteurization (Fuleki and Ricardo-da-silva, 2003).Total gallotannin concentration decreases in mangoes with the increasing hot water temperature because the biosynthesis of gallotannins proceeds in the presence of galloyltransferases during thermal treatment (Kim et al., 2009). However, hydrolysable tannin is unaffected by the hot water treatment of mangoes (Kim et al., 2007).

Concentrations of various flavanones, flavones, and flavanols are higher in lemon powder after microwave-assisted extraction than after shaking extraction because more flavonoids are extracted from cells after treatment with microwaves (Ledesma-Escobar et al., 2016). However, Igual et al. (2011) showed that flavonoid contents (narirutin, naringin, hesperidin, neohesperidin, didymin, poncirin, naringenin, and quercetin) of grapefruit juice are not significantly different between conventionally and microwave-pasteurized juices. However, microwave pasteurization yielded the greatest flavonoid retention in frozen state than did conventional pasteurization (Igual et al., 2011). Similar results were obtained for total flavonoid content

Table 1. Impact of thermal processing on flavonoids content of fruits.

Fruits	Product type	Processing conditions	Name of flavonoids	Impact on flavonoids content	References
Litchi	Juice	Blanched for 30 s in 100°C; heated at 100°C for 60 s by water bath and 134°C for 4 s by heat exchanger	(−)-epicatechin, rutin and total flavonoid content	↑All flavonoids content	Liu et al. (2015)
Açai fruit	Purees	Temperature at 80°C for 1, 5, 10, 30, or 60 min.	Orientin and isoorientin, isovitexin, scoparin, isovitexin, taxifolin, luteolin, (+)-catechin or (−)-epicatechin, and apigenin glycosides	↔All flavonoids content	Pacheco-Palencia et al. (2009)
Mango	Whole fruit	80°C for 8 min in hot water	Total flavonoid	↑ Total flavonoid	Nohemi et al. (2012)
Ber fruit	Whole fruit, beverage	80°C for 8 min in hot water	Total flavonoid	↑Total flavonoid	Kavitha and Kuna (2014)
Whole campbell grape	Juice	Microwave heat treatment), blanching and ultrasonication (1–5 min)	Total flavonoid	Depending on blanching time	Cabrera and Moon (2015)
Apple	Pomace	Blanched and unblanched pomace samples were dehydrated at temperatures of 50, 60, 70, and 80°C using cabinet dryer	Total flavonoid, (+)-catechin, rutin, phloridzin, (−)-epicatechin	↔All flavonoids content	Heras-Ramírez et al. (2012)
Strawberry	Juice	Pasturized (90°C for 30 s and 60 s)	Kaempferol, quercetin, myricetin	↔All flavonoids content	Odriozola-Serrano et al., (2008)
Grape	Juice	Pasteurized at 90°C for 1 min	Catechin	↔Catechin content	Marsellés-Fontanet et al. (2013)
Tomato	Juice	Pasturized (90°C for 30 and 60 s)	Quercetin, kaempferol	↓All flavonoids content	Odriozola-Serrano et al., (2009)
Pineapple	Juice	Pasteurization (97°C for 5 min)	Total flavonoid	↑Total flavonoid	Goh et al. (2012)
Orange	Juice	Heated at 80°C for 30 min and 90°C for 30 s in a water bath	Naringin, hesperetin-rutinoside, naringenin-trisaccharide, luteolin-rutinoside, quercetin-trisaccharide	↑Lower temperature all flavonoids content ↓ Higher temperature all flavonoids content	He et al. (2016)
Grape	Juice	Heated at 80°C for 30 min and 90°C for 30 s in a water bath	Epicatechin, proanthocyanidin	↑ All flavonoids content (at lower temperature) ↓All flavonoids content (At higher temperature)	He et al. (2016)
Apple	Juice	Heated at 80°C for 30 min and 90°C for 30 s in a water bath	Hesperidin, phloridzin, epigallocatechin gallate	↑All flavonoids content (at lower temperature) ↓All flavonoids content (at higher temperature)	He et al. (2016)
Orange	Juice	Heated at 70°C for 30 s	Naringenin, hesperetin	↓Naringenin and hesperetin content	Plaza et al. (2011)
Cran berry	Juice	Pasteurization (90°C for 90 s)	Proanthocyanidins	↓Naringenin and hesperetin content	Giacarini (2008)
Orange	Juice	Heated at 35°C, 30 min and 70°C for 30 s by autoclave	Naringenin, hesperetin, total flavanones	↑Hesperetin content ↓Naringenin content	Sanchen-moreno et al. (2005)
Orange, mango, kiwi and pineapple	Fruit juice-milk beverages	Pasteurized at 90°C for 1 min	Total flavonoid content, hesperidin, rutin, narirutin and quercetin	↑All flavonoids content	Morales-delapena et al. (2016)
Orange, kiwi and pineapple	Fruit juice–soymilk	Pasteurized at 90°C for 60 s	Hesperidin, rutin, narirutin, quercetin, and apigenin	↑All flavonoids content	Morales-dela Peña et al. (2011)
Orange (25%), kiwi (18%) and pineapple	Fruit juice-soymilk beverage	Pasteurized at 90°C for 60 s	Daidzein, genistein, daidzin, and genisitin	All flavonoids content↑	Morales-delaeña et al. (2010)
Orange	Juice	Pasteurization (90°C/1 min)	Narirutin Hesperidin Eriocitrin Eriodictyol Naringenin Hesperetin Kaempferol	↑Hesperetin content ↓ Other flavonoid content	Estrada (2011)
Prickly pears	Juice	Heat sterilization (131°C for 2 s).	Quercetin, kaempferol, and isorhamnetin contents	↓All flavonoids content	Jiménez-Aguilar et al. (2015)

(*Continued on next page*)

Table 1. (Continued).

Fruits	Product type	Processing conditions	Name of flavonoids	Impact on flavonoids content	References
Grape	Seed	Sterilized (120°C for 20 min), cooked (93 ± 2° C for 30 min), and baked (180 ± 2°C for 90 min)	(+)-Catechin, (−)- gallocatechin, (−)-epicatechin, (−)-epicatechingallate, (−) epigallocatechin gallate, (−)-epigallocatechin (EGC), condensed tannin and procyanidins	↑All flavonoids content	Davidov-Pardo et al. (2011)
Aonla fruits	Shreds	Blanching with boiling water for 3 min Blanching with 0.1% KMS for 3 min and dried with solar and hot air drying	Tannin	↑ Tannin content	Prajapati et al. (2011)
Mandarin	Peel powder	Blanched at (90°C for 1 min)	Tannin	↓Tannin content	Ojha et al. (2016)
Pitanga	Pulp and fresh	Pasteurized	Myricetin, quercetin, and kaempferol	↑All flavonoids content	Hoffmann-Ribani et al. (2009)
Grape	Juice	Pasteurized	(+)-Catechin, (−)-epicatechin, and nine procyanidins	↑In cold-pressed juice all flavonoids content ↓In hot-pressed juice all flavonoids content	Fuleki and Ricardo-da-Silva (2003)
Grape and plum	Peels	At 70°C held during 1 h	Total falvonoids	↑All flavonoids content (for grape) ↓All flavonoids content (for plum)	Medina-Meza and Barbosa-Cánovas (2015)
Orange	Juice	Heated at 90°C for 10 and 20 s	Flavonones, flavonols, flavones	Variable individual flavonoid content	Agcam et al. (2014)
Grape	Seed	Pasteurized (65 ± 2°C for 30 min, and 75 ± 1°C for 20 s)	(+)-Catechin, (−)- gallocatechin, (−)-epicatechin, (−)-epicatechingallate, (−)-epigallocatechin gallate, (−)-epigallocatechin (EGC), condensed tannin and procyanidins	All flavonoids content	Davidov-Pardo et al. (2011)
Mulberry	juice	Heated at 85°C for 15 min by water bath	Total falvonoid	↓Total falvonoid	Wang et al. (2016)
Mulberry	juice	Heated at 95°C, 1 min	Quercetin aglycone	↓Quercetin aglycone	Yu et al. (2014)
Mango	Juice	At 90°C for 60 s with shaking	Total flavonoid content	↓Total flavonoid content	Santhirasegaram et al. (2015)
Açai fruit	Pulp and Juice	Pasteurized with ascorbic acid and stored at 4 and 20°C	(+)-Catechin, (−)-Epicatechin, procyanidin-1, procyanidin-2, procyanidin polymer-1, procyanidin polymer-2	Minor changes the flavonoid content	Pacheco-Palencia et al. (2007)
Mango	Whole fruit	Blanched at (70, 90, and 100°C for 70 min)	Total gallotannin	↓Total gallotannin	Kim et al. (2009)
Mango	Whole fruit	Blanched at (46.1°C for 75 min)	Total hydrolysable tannin	↔Total hydrolysable tannin	Kim et al. (2007)
Lemons	Powder	Microwave-assisted extraction (six extraction cycles; 68% ethanol in water; and 170 W) and shaking extraction (60 min: 60% ethanol in water)	Various flavanones, flavones, and flavanols content	Flavonoid content depending on extraction methods	Ledesma-Escobar et al. (2016)
Grapefruit	Juice	Conventional pasteurized (85 ± 2.5°C for 11 s) and microwave pasteurized (85 ± 2.5°C for 30 s at 900 MW)	Narirutin naringin, hesperidin, neohesperidin, didymin, poncirin, naringenin, and quercetin	↔All flavonoids content	Igual et al. (2011)
Oange	Peels	Microwave assisted extraction (heated for 180 s at 100, 200, 300, or 400 W)	Total flavonoid and different individual flavonoid.	Depending on microwave power	M'hiri et al. (2015)
Cactus fruit	Juice		Flavonol glycoside (isorhamnetin-3-O-rutinoside content)	↑Flavonol glycoside	Moussa-Ayoub et al. (2016)

		Microwave heating (at 1800 W) up to 90°C with a holding time of 3 min and subsequent cooling.			
Campbell grape	Juice	Microwave heat treatment blanching and ultrasonication (1–5 min)	Total flavonoid	↑Total flavonoid	Cabrera and Moon (2015)
Apple	Juice	Heated at 40, 50, 60, and 70°C in a 2450 MHz microwave oven at 1500 W	Total flavonoid	↑Total flavonoid	Gerard and Roberts (2004)
Grape and blueberry	Pomace	Heated in a forced air oven at 40, 60, 105, and 125°C for 72, 48, 16, and 8 h, respectively	Monomer, dimer, trimer, tetramer, pentamer, hextamer, heptamer, and polymer	Depending on temperature and time	Khanal et al. (2010)
Red grape	Pomace peels	Freeze dried and hot air dried (60, 100, and 140°C)	Condensed tannin	↑Condensed tannin	Larrauri et al. (1997)
Apple	Cubes	Drying temperatures of 30, 50, and 70°C	Total flavonoid	Depending on temperature	Rodríguez et al. (2014)
Lemons	Powder	Lyophilized or air-dried (45°C)	Various flavanones, flavones, and flavanols content	Depending on drying methods	Ledesma-Escobar et al. (2016)
Cashew	Whole, kernel and testa	Dried by hot air (70°C for 6 h and 130°C for 33 min)	Proanthocyanidin, (+)-catechin, (−)-epicatechin, and epigallocatechin.	↑Catechin, epicatechin, and epigallocatechin at higher temperature	Chandrasekara and Shahidi (2011)
Litchi	Litchi pericarps	Steam blanching for 3 min and hot air oven drying at 60 and 80°C, hot air oven drying (40, 60, 70, and 80°C)	Total flavonoid, procyanidin A2, procyanidin B2, epicatechin, catechin	Depending on conditions	Kessy et al., (2016)
Tomatoes	sliced	Fried: 5 min; boiled: 15 min; microwaved: 1.3 min	Quercetin	↑Quercetin	Crozier et al. (1997)
Straw berries	Jam	Cooked 30 min	Quercetin, kaempferol	↓Quercetin, kaempferol	Hakkinen et al. (2000)
Bilberries	Soup	Cooked 10 min	Quercetin	↓Quercetin	Hakkinen et al. (2000)
Pear	Whole fruit	Boiled (82–85°C for 30 min)	Flavan-3-ols	↓Flavan-3-ols	Renard (2005)

↓, Decreased; ↑, increased; ↔, unchanged.

Table 2. Impact of thermal processing on flavonoids content of vegetables.

Vegetables	Product type	Processing conditions	Name of flavonoids	Impact on flavonoids content	References
Boerhaavia diffusa and Portulaca oleracea	Powder	Boiled in water at 100°C for 15 min in the ratio of 1:10 (w/v). Blanched in boiling water (at 100°C) for 10 min in the ratio of 1:10 (w/v).	Total flavonoid and Tannins content	Depending on conditions	Nagarani et al. (2014)
Chaya leaf	Raw	Blanched at 65°C for 16 min, boiled at 100°C for 15 min.	Tannin	↓ Tannin	Babalola and Alabi (2015)
Yam Bean	Raw	Blanched (100°C for 20, 30, and 40 min), soaked with distilled water, sodium chloride (0.2, 0.4, 0.5, and 1.0%), and sodium bicarbonate solutions (0.2, 0.4, 0.5, and 1.0%) at room temperature for 6 and 12 h.	Tannin	↓ Tannin	Aminigo and Metzger (2005)
Black carrots	Raw and powder	Blanched at 98°C temperature for 3 min. Chemical pretreatments done with calcium chloride solution 1:2 (w/v) 3.5 g citric acids in 1 L water, KMS solution 2:1 L (w/v) water for 15 min at room temperature.	Total flavonoid content	↓Total flavonoid content	Garba and Kaur (2014)
Brussels sprouts	Raw	Immersion in water at 50°C for 5 min followed by blanching in boiling water for 3 min, immersion in water (100°C) 1, 3, and 4 min and microwave heating at 700 W for 5 min, followed by blanching in boiling water for 2 min.	Total flavonoids content	↓Total flavonoid content	Vina et al. (2007)
Celery plants	Pre-cut celery	Immersion in water at 50°C for 90 s dry-heated air (oven) at 48°C for 1 h.	Total flavonoids content	↓Total flavonoid content	Vina and Chaves (2008)
Onions, green beans, and peas	Raw	Steam blanched, boiled 3 min, microwave (65 W for 3 min) fried with rape seed oil for 5 min, drying at 60°C for 1 and 2 h.	Quercetin and Kaempferol	↓Quercetin and kaempferol	Ewald et al. (1999)
Brassica vegetables	Raw	Blanched and chilled at room temperature for about 15 min, cooked and chilled, and frozen (blanched, chilled and stored for 48 h at −22°C) vegetables, cooking after freezing for about 10 min	Quercetin, kaempferol, isorhamnetin	↓Quercetin, kaempferol, isorhamnetin	Sikora et al. (2012)
Leafy vegetables	Raw	Blanched at 100°C for 5 min,	Total flavonoids	↓Total flavonoids	Salau et al. (2015)
Garlic and white and red onions	Powder	Blanched (in water at 100°C for 90 s), boiled (10 min) and fried (100°C during 10 min)	Flavonoids, flavanols, and tannin	↓Flavonoids, flavanols, and tannin	Gorinstein et al. (2008)
Chaya leaf	Raw	Blanched at 65°C for 16 min, boiled at 100°C for 15 min	Total flavonoids	↓Total flavonoids	Babalola and Alabi (2015)
Garlic	pastes	Pasteurization at 90°C for a time of 5 min.	Total flavonoid contents	↓Total flavonoids	Unni et al. (2014)
York cabbage	Raw	Blanching was carried out between 80 and 100°C for 2 min to 14 min.	Total flavonoids content	↓Total flavonoids	Jaiswal et al. (2012)
Brussels sprouts	Raw	At 700 W for 5 min, followed by blanching in boiling water for 2 min.	Total flavonoids content	↑Total flavonoids content	Olivera et al. (2008)
Lemon grass	Raw	At 100°C for 10 minutes cold extraction in water for 10 min	Total flavonoids content	↑Total flavonoids content	Oboh et al. (2010)
Sweet potato	Raw	Blanched at 100°C for 0 to 120 min.	Myricetin, quercetin, apigenin	↓Myricetin, quercetin, apigenin	Chu et al. (2000)
Black gram	Raw	Tap water or different salt solutions at either 30°C for 1 to 3 h or 100°C for 15 to 45 min.	Tannins content	↓Tannins content	Rehman and Shah (2001)
Pinto and BlackBeans	Raw	Regular boiling 80 and 90 min; pressure boiling 15 psi, 10 min, regular steaming, 70 min pressure steam in 15 psi, 10 min.	(+)-Catechin, (+)-epicatechin, epicatechin gallate, kaempferol-3-O-glucoside, kaempferol-3-O-acetylglucoside myricetin	Depending on conditions	Xu and Chang (2009)
Spinach, mushroom, cluster beans, drumstick, and beetroot	Raw	Sautéing, boiling, and pressure cooking	Total flavonoids	↓Total flavonoids	Rani and Fernando (2016)
Brazilian bean	Raw			↑Without soaking	Ranilla et al. (2009)

(*Continued on next page*)

Table 2. (Continued).

Vegetables	Product type	Processing conditions	Name of flavonoids	Impact on flavonoids content	References
		With or without soaking, at atmospheric (100°C) or pressure boiling (121°C)	Quercetin derivatives, and kaempferol derivatives		
Brussels sprouts	Frozen	Immersion of sprouts in water at 100°C for 4 min and immersion in water at 50°C for 5 min followed by blanching in boiling water for 3 min.	Total flavonoids content	↔Total flavonoids content	Olivera et al. (2008)
Green broccoli	Raw	Cooked for 5, 10, and 20 min,	Total flavonoids content	↓Total flavonoids content	Porter (2012)
Purple-sprouting broccoli	Raw	Microwave oven on a high heat for 1, 2, and 5 min	Total flavonoids content	↑Total flavonoids content	Porter (2012)
Broccoli and cauliflower	Raw	Boiling at 100°C for 5 min, steaming, for 20 min and for the microwave at 800 W for 4 min	Quercetin and kaempferol	↓Boiling Quercetin and kaempferol ↑Steaming kaempferol	Ramos dos Reis et al. (2015)
Cauliflower	Raw	Boiling water and cooked for 6 min. Steam boiling, 6 min 15 s, microwave oven for 3 min 30 s tir-Frying. Heated (140 ± 2°C) with sunflower oil (10 mL) for 4 min 30 s	Total flavonoids content	↓Total flavonoids content	Ahmed and Ali (2013)
Red onion	Raw	Microwave (245 MHZ frequency, power 1200 W for 4 min) steam blanched (15 and 20 min), boiling (100°C for 16 and 18 min), frying with oil at 180°C for 4 and 8 min	Total flavonoids and tannin content	↑Total flavonoids and tannin content	Laib and Barkat (2016)
Onion bulbs	Raw	Microwave (450 W and 4 min, 750 W and 4 min), oven (180°C and 15 min, 200°C and 30 min), boiling (103°C for 30 min and 60 min), frying with oil at 180°C for 4 and 8 min	Quercetin (3, 4′-quercetin-O-diglucoside and 4′-quercetin-O-glucoside)	Depending on microwave power	Rodrigues et al. (2009)
Onion bulbs and asparagus spears	Raw	Boiled for 60 min in 400 mL of tap water, pH 6.98–7.04 and chopped carefully into small pieces (approximately 0.5-cm length) with a sharp knife	Quercetin 3,4′-diglucoside, quercetin 4′-glucoside, free quercetin	↓ Quercetin 3,4′-diglucoside, quercetin 4′-glucoside, free quercetin	Makris and Rossiter (2001)
Onion	Raw/slice	Sauté (preheated to 93°C and oil was allowed to warm for 1 min and onion slices were sautéed for 5 min, bake (at 176°C for 15 min), boil (5 min)	3,4′-Quercetin-O-diglucoside; 4′-quercetin-O-glucoside	↓3, 4′-Quercetin-O-diglucoside; 4′-quercetin-O-glucoside.	Lombard et al. (2005)
Onion bulbs	Raw	Boiled for 1 h	Flavonol glycosides and flavonol aglycon	↓Flavonol glycosides and flavonol aglycon	Hirota et al. (1998)
Sweet and hot chilli pepper	Raw	Boiled at 100°C in a covered pan (containing water in an approximate ratio of 1:1, w/v fruit to water), for 15 min	Total flavonoids content	↑ Total flavonoids content	Shaimaa et al. (2016)
Carrot and spinach	Carrot shredded into small piece, Spinach	Carrot and spinach parboiled for 7 and 5 min, respectively	Total flavonoid contents	↑Total flavonoid contents	Jung et al. (2013)
Broccoli	Raw	Steamed for 5 and 10 min	Total flavonoids content	↑Total flavonoid contents	Roy et al. (2009)
Sweet potatoes	Raw	Steam blanched 40 min.	Total flavonoids	↓Total flavonoids	Huang et al. (2006)
Mushroom	sliced	Heated at 100°C and 121°C for 15 and 30 min	Total flavonoids content	↑Total flavonoid contents	Choi et al. (2006)
Onion	Powder	Heated at 80, 100, 120, and 150°C for 30 min	Quercetin aglycone, quercetin-3-4′-O-monoglucoside, quercetin-3, 4′-odiglucoside, and isorhamnetin-3-glucoside	Depending on heating temperature	Sharma (2015)
Red and brown onion	Raw	Boiling for 20 min, frying with sunflower oil for 5 and 15 min	Flavonol glucosides	↓Flavonol glucosides	Price et al. (1997)
Centella asiatica	Raw leaf, root and petiole	Freeze drying, hot air drying (45°C for 48 h) Vacuum oven-drying method (45°C for 5 h)	Flavonol (quercetin, myricetin, kaempferol), catechin, flavones (apigenin, luteolin), and flavanone (naringin)	↑Freeze drying	Mohd Zainol et al. (2009)

↓, decreased; ↑, increased; ↔, unchanged.

in orange peel and cactus fruit juice after microwave extraction (M'hiri et al., 2015; Moussa-Ayoub et al., 2016). Usually, more falvonoids can be released from cells after treatment with microwaves. M'hiri et al. (2015) stated that lower microwave power is more suitable for extraction of individual flavonoid content from orange peel than higher microwave power because of increased glycosylated flavonoid contents. Cabrera and Moon (2015) found that microwave heat treatment of whole Campbell grapes before processing can increase total flavonoid content because of polyphenoloxidase inactivation.

There are a nonsignificant difference in terms of tannin between different types of drying methods (solar and hot air drying) for anola shreds (Prajapati et al., 2011). The extraction of total flavonoid content is enhanced in apple mash treated with microwave heating before juice extraction (Gerard and Roberts, 2004): probably the bound flavonoid content is released more readily due to disruption of cells during microwave heating. Drying temperature has no significant effect on individual flavonoid contentin apple pomace in a comparison between blanched and unblanched samples (Heras-Ramírez et al., 2012). However, notable losses of (+)-catechin, rutin, phloridzin, and (−)-epicatechin were observed at a higher temperature (80°C) than at a lower temperature (50°C) in both blanched and unblanched samples. This phenomenon might be related to the formation of degradation products, as reported by Heras-Ramírez et al. (2012). However, Khanal et al. (2010) mentioned that levels of individual procyanidin monomers depend on heating temperature and the pomace type caused by formation of oligomers or polymers. Freeze-dried samples of red grape pomace peels had higher tannin content as compared to hot-air-dried samples. On the other hand, the decrease rate of condensed tannin is higher (16.6%) at a higher drying temperature (140°C), followed by drying at a lower temperature (100°C). Perhaps thermal degradation is more pronounced during hot air drying as well as at a higher temperature (Larrauri et al., 1997). Lower drying temperature (30°C) showed a lower loss of flavonoid content in apple slices in comparison with slices dried at 70°C because heat can cause more damage to flavonoid content (Rodríguez et al., 2014). Lyophilized samples show higher amounts of neodiosmin and neohesperidin, while limocitrin-HMG-Glu and limocitrol-Glu-HMG concentrations are found to be higher in both fresh and air-dried samples (Ledesma-Escobar et al., 2016). These authors stated that lemon metabolism is more pronounced in lyophilized samples whereas enzymatic reactions are more active in a hot-air sample. Chandrasekara and Shahidi (2011) demonstrated that roasting at a lower forced hot-air temperature (70°C for 6 h) decreases proanthocyanidin content whereas catechin, epicatechin, and epigallocatechin contents increase at a higher roasting temperature (130°C for 33 min) in cashew nuts in comparison with raw nuts. They mentioned that tannin content decreased due to the enhanced polymerisation process, thus the proanthocyanidin content decreased. However, individual flavonoid compound structure may change during thermal processing: this may be the reason for increased flavonoid content. Another study showed that steam blanching and oven drying at 60°C yield higher total flavonoid content and total procyanidin content in litchi pericarps as compared to fresh and hot-air-dried samples (40, 60, 70, and 80°C); it is possible that the combination of steam blanching and oven drying causes greater inactivation of oxidative enzymes (Kessy et al., 2016).

Cooking by frying produces higher quercetin content in tomatoes, followed by microwave treatment and boiling. It is possible that quercetin is concentrated during frying (Crozier et al., 1997). Approximately 15% of quercetin and 18% of kaempferol are lost after cooking of strawberry jam, whereas 40% of quercetin is lost during cooking of bilberry soup (Hakkinen et al., 2000), and a similar finding was mentioned for quercetin in cooked tomatoes (Crozier et al., 1997). Another study also revealed that flavan-3-ols are reduced in pears after 20 min of cooking (Renard, 2005). It is possible that flavonoids breakdown or leach out during cooking (Crozier et al., 1997). On the other hand, baking (180°C for 90 min) yielded a higher total amount of identified compounds (tanin, catechin, gallocatechin, epicatechin, epicatechingallate, epigallocatechingallate, epigallocatechin, and procyanidins) in grape seed relative to cooking (93°C ± 2°C for 30 min) (Davidov-Pardo et al., 2011) because baking may concentrate some flavonoid compounds.

The effect of thermal processing on flavonoid content of vegetables

Blanched and boiled samples of two leafy vegetables (Boerhaavia diffusa and Portulaca oleracea) have higher total flavonoid content, whereas boiled samples of B. diffusa vegetables have higher tannin content than control does. However, tannin content is lower in a boiled sample of P. oleracea as compared to control (Nagarani et al., 2014). Blanching treatment yields lower tannin content in chaya leaf (Babalola and Alabi, 2015) and yam bean seed and flower (Aminigo and Metzger, 2005) in comparison with fresh samples. It is known that cells can be disrupted during thermal processing; hence, some flavonoid compounds are released. Subsequently, higher iron-chelating activity might be responsible for high tannin content (Nagarani et al., 2014). However, blanching has detrimental effects on total flavonoid content in black carrot (Garba and Kaur, 2014), Brussels sprouts (Vina et al., 2007), pre-cut celery (Vina and Chaves, 2008), onion (Ewald et al., 1999), brassica vegetables (Sikora et al., 2012), sweet potato leaf (Salau et al., 2015), red and white onions (Gorinstein et al., 2008), chaya leaf (Babalola and Alabi, 2015), and garlic (Unni et al., 2014) because of leaching out of some flavonoids. A blanched sample showed 74.4–78.0% lower flavonoid content in Irish York cabbage (Jaiswal et al., 2012). Blanching can increase total flavonoid content in Brussels sprouts after 8 months of storage relative to that on the initial day at −18°C. The increased concentration is related to combined effects of blanching, freezing, and frozen storage (Olivera et al., 2008). Hot water blanching yields higher flavonoid content in Lemon grass than does cold water blanching (Oboh et al., 2010). Various blanched leafy vegetables retain higher flavonoid content as compared to fresh ones (Salau et al., 2015). Inactivation of enzymes is the main reason for increased flavonoid content. However, myricetin, quercetin, and apigenin content in sweet potato leaves decreases with increased blanching duration because some flavonoid content can be transferred into water (or enzymatic activity was responsible) (Chu et al., 2000). Soaking temperature and time reduce

the tannin content of black grams in comparison with control. The reduction rate increased with the increase in soaking temperature and time owing to leaching out of tannin (Rehman and Shah, 2001).This research group demonstrated that soaking in tap water yields higher content of tannin than soaking in other solutions such as sodium chloride and sodium bicarbonate because some tannin content is solubilized. Similar results were obtained for tannin content when samples were cooked in a pressure cooker. Regular and pressure steaming preserves more individual flavan-3-ols, flavonols, and total flavonols in pinto and black beans as compared to regular and pressure boiling because boiling promotes leaching out of greater flavonoid amounts than steaming does (Xu and Chang, 2009). Pressure cooking also drastically reduces the total flavonoid content in spinach, mushroom, cluster beans, drumstick, and beetroot (Rani and Fernando, 2016). Cooking at 100 or 121°C without soaking and without draining can increase quercetin and kaempferol content in beans relative to that with soaking and with draining or in comparison with raw beans. Perhaps, some flavonoids are drained out during soaking and draining. In addition, cooking releases more flavonoids from the food matrix (Ranilla et al., 2009).

A microwave-treated sample showed lower total flavonoid content in Brussels sprouts, although the value was not significantly different during storage at −18°C (Vina et al., 2007; Olivera et al., 2008). However, microwave treatment reduced total flavonoid content by 59.77% in purple sprouting broccoli; additionally, microwaving had no effect on the flavonoid content in green broccoli as compared to that in fresh broccoli (Porter, 2012). A reduction in flavonoid content was observed in broccoli, cauliflower, onion, green beans, and peas after microwave processing (Ewald et al., 1999; Ahmed and Ali, 2013; Ramos dos Reis et al., 2015). Nevertheless Laib and Barkat (2016) reported that microwave treatment yields higher total flavonoid and tannin content in red onion relative to untreated samples. Intense microwave cooking causes a greater loss of quercetin 3,4-diglucoside and quercetin 4-glucoside content in onion bulbs than does moderate microwave cooking (Rodrigues et al., 2009).

Flavonoid content in purple sprouting broccoli is reduced by 59.77% after boiling whereas there are no significant differences in flavonoid content of green broccoli between boiled and fresh samples (Porter, 2012). A flavonoid content reduction was observed in onions (20.6%), in asparagus (43.9%) (Makris and Rossiter, 2001), in cauliflower (56.39%) (Ahmed and Ali, 2013), and in onion (18%) (Lombard et al., 2005) after boiling. Boiling also degrades the flavonoid content in onion, green beans, and peas (Ewald et al., 1999), onion bulbs (Hirota et al., 1998), brassica vegetables (Sikora et al., 2012) chaya leaf (Babalola and Alabi, 2015), spinach, mushroom, cluster beans, drumstick, and beetroot (Rani and Fernando, 2016). However, Shaimaa et al. (2016) found that boiling can increase flavonoid content in sweet and hot chilli peppers; besides, naringin, heisperdin, and quercetin contents are also higher in ethanolic extract as compared to aqueous and boiling water extract. Similar results were obtained by Laib and Barkat (2016), who showed that boiling can raise the flavonoid content in red onion. An increase in kaempferol content was observed in broccoli; a decrease in quercetin and kaempferol content was also detected in cauliflower and a decrease in quercetin content in broccoli after boiling (Ramos dos Reis et al., 2015). Thermal treatment (parboiling) increases the flavonoid content in carrot and spinach (Jung et al., 2013), whereas thermal treatment significantly reduces the flavonoid content of garlic (Unni et al., 2014). The loss of flavonoid content in onion bulbs increases with the increase in boiling duration (Rodrigues et al., 2009). Tannin content is also reduced in chaya leaf (Babalola and Alabi, 2015) after boiling.

Steam processing of a hydrophilic extract yields higher flavonoid content in broccoli in comparison with a fresh and lipophilic extract (Roy et al., 2009). Another study showed that kaempferol content in broccoli is higher whereas quercetin content in broccoli is lower after steam processing (Ramos dos Reis et al., 2015). Steam blanching also increased the total flavonoid and tannin content in red onion as compared to untreated samples (Laib and Barkat, 2016). Steaming treatment decreases the total flavonoid content in most of sweet potato varieties even though one variety has a higher total flavonoid concentration than untreated samples do (Huang et al., 2006).

Drying and frying also reduce the flavonoid content in precut celery (Vina and Chaves, 2008), cauliflower (Ahmed and Ali, 2013) onion, green beans, and peas (Ewald et al., 1999) in comparison with control. Heat treatment markedly increases the total flavonoid content in mushrooms (Choi et al., 2006). Sharma (2015) reported that flavonoid content in different onions can vary with heating temperature. Baking and sauté cooking (heat treatment) also increase the total flavonoid and quercetin (3,4′-quercetin-O-diglucoside; 4′-quercetin-O-glucoside) content in onion (Lombard et al., 2005). Sauté heat treatment also degrades the flavonoids in spinach, mushrooms, cluster beans, drumsticks, and beetroot (Rani and Fernando, 2016). Frying and oven drying do not affect flavonoid content in onion bulbs (Rodrigues et al., 2009). Quercetin glucoside content in red- and brown-skinned onions decreases with the increase in frying time (Price et al., 1997). Freeze drying yielded higher quercetin, myricetin, kaempferol, catechin, apigenin, luteolin, and naringin content in Centella asiatica, followed by vacuum oven and air oven drying (Mohd Zainol et al., 2009). This research group reported that drying has a detrimental effect on flavonoind content in Centella asiatica in comparison with fresh samples.

There are numerous causes behind increased or reduced flavonoid content in vegetables during thermal processing. A few reasons were already mentioned in the earlier sections. However, some are listed below: (i) Heating can disrupt the cells as well as deactivate endogenous oxidative enzymes hence flavonoid content will increase (Choi et al., 2006). Heating also may interfere with the metabolisim of a plant there by influencing the flavonoid content (Sharma, 2015). (ii) Breakdown of flavonoids with increasing time and temperature further affects the flavonoid content during thermal processing (Mohd Zainol et al., 2009). (iii) Sometimes flavonoids are very water-soluble because flavonoids exist as glycosides (Mohd Zainol et al., 2009). (iv) Various types of enzymes, light, and oxygen play important roles in retention of flavonoid content during processing. (v) The number and position of hydroxyl groups can change during thermal treatment, thus causing the disparities in flavonoid content (Mohd Zainol et al., 2009).

Nonthermal processing

At this time, the food industry owners prefer nonthermal processing like high hydrostatic pressure, pulsed electric field, ultrasound, ultraviolet rays, irradiation, ohmic heating, ozone processing, and dense-phase carbon dioxide rather than thermal processing in order to minimize the losses of phytochemicals as well as to obtain safe and nutritionally rich products. Usually nonthermal processing on a large scale is applied to fruits rather than vegetables. Commonly, high hydrostatic pressure, pulsed electric field, ultrasound, and ultraviolet rays are also used in the food sector. Each and every nonthermal processing technique has some processing parameters that could influence the product quality. Usually, for high-pressure processing, pressure of 0–1000 MPa is applied to food. Thus, hydrostic pressure, temperature, and duration are crucial factors of high hydrostatic pressure processing of food (Ferstl and Ferstl, 2013). However, field strength, treatment time, treatment temperature, pulse shape, the species of a microorganism, growth stage of the microorganism, and characteristics of the treatment substrate are main parameters for pulsed electric field processing (Mohamed and Amer Eissa, 2012). Pingret et al. (2013) mentioned that during ultrasound processing, frequency, wavelength, and amplitude of the wave; ultrasonic power; and consequent intensity should be optimized, otherwise processing can be affected. For the UV technology, wavelengths 100 to 400 nm are used for food processing. The success of the UV technology depends on a UV nanometer, UV light source, duration, and types of food (Koutchma, 2009). Figures 5–7 and 8 show the schematic diagram of high hydrostic pressure, pulsed electric field, ultrasound, and UV technologies, respectively. Effects of nonthermal treatments on flavonoid content of fruits and vegetables are shown in Tables 3 and 4, respectively.

Effect of nonthermal processing on flavonoid content of fruits

High-pressure homogenization processing at 250 MPa for 10 min was used to prepare apple, orange, and grape juice and to evaluate the effects of high pressure on individual flavonoid content (He et al., 2016). They found that hesperidin, phloridzin, and epigallocatechin gallate content was decreased in apple juice whereas naringin, naringenin-trisaccharide, luteolin-rutinoside, and quercetin-trisaccharide contents were increased in orange juice. The same authors also mentioned that after high-pressure treatment, proanthocyanidin concentration could be increased, and epicatechin concentration might be decreased in grape juice whereas hesperetin-rutinoside content showed a decreasing trend in orange juice. An increase in individual flavonoid contents is attributed to the rupture of cellular structure and a decrease in the concentration of a few flavonoids might be related to oxidation, epimerization, and degradation of the fruit polyphenols (He et al., 2016). Although naringin has antioxidant, anti-inflammatory, antiulcer, and hypocholesterolemic effects, it also has unique characteristics: bitterness in citrus juice (Ferreira et al., 2008). These authors revealed that naringin reduction by 75% was observed in a model solution at 37°C under high pressure of 160 MPa for 20 min, whereas a 35% reduction was observed at atmospheric pressure (0.1 MPa) owing to greater amounts of reducing sugars formed by high pressure processing.

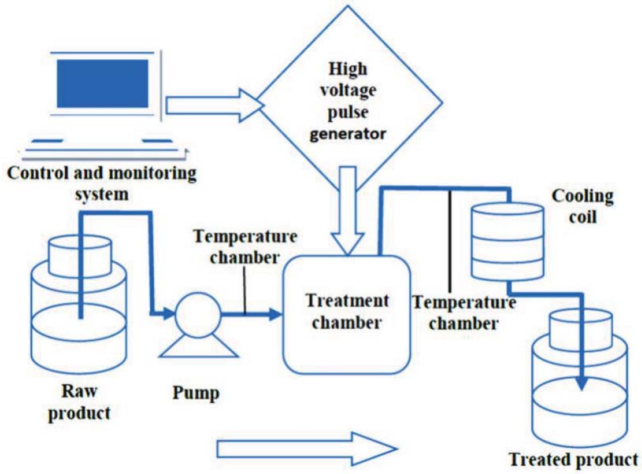

Figure 6. Schematic representation of pulsed electric field processing (adapted from Mohamed and Amer Eissa, 2012).

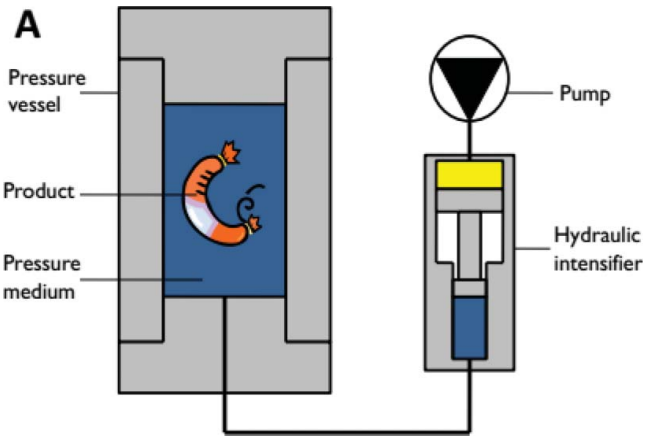

Figure 5. Schematic representation of high-pressure processing (adapted from Ferstl and Ferstl, 2013).

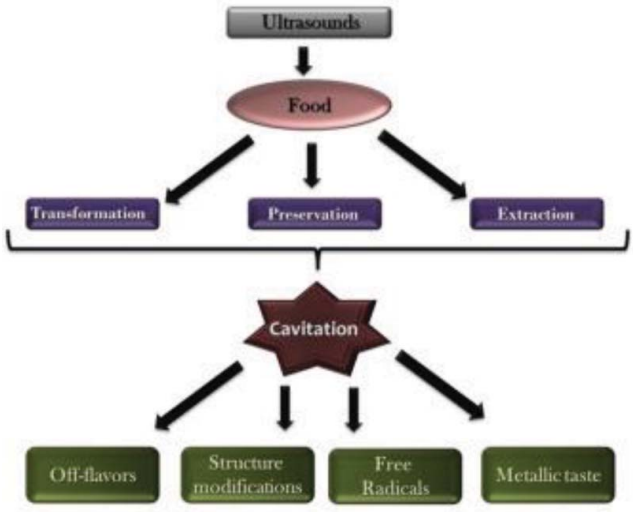

Figure 7. Schematic representation of ultrasound in food processing (adapted from Pingret et al., 2013).

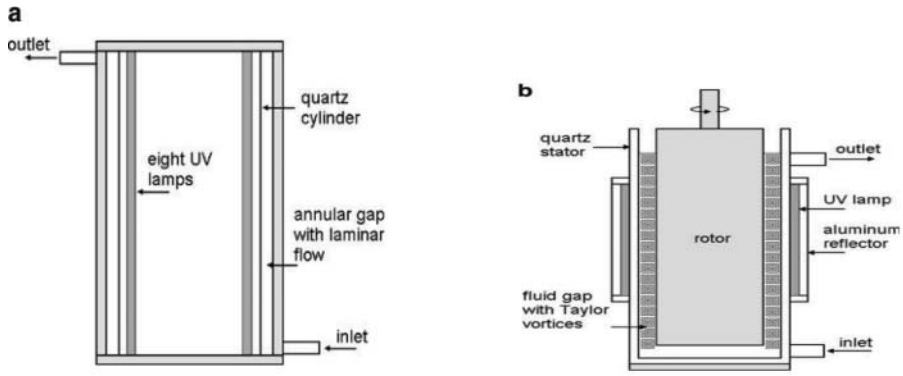

Figure 8. Schematic representation of the UV technology: (a) a laminar thin film reactor; (b) Taylor–Couette flow (adapted from Koutchma, 2009).

Naringenin and hesperetin contents were significantly increased just after treatment with high pressure processing relative to untreated orange juice. A similar tendency was observed for up to 20 days later: individual flavonoid contents declined as compared to untreated samples during storage at 4°C (Plaza et al., 2011). Higher pressure (400 MPa/40°C/1 min) raised naringenin and hesperetin content in orange juice in comparison with untreated and lower pressure (100 MPa/60°C/5 min and 350 MPa/30°C/2.5 min)-treated samples (Sánchez-Moreno et al., 2003). This research group found that bound flavonoids are probably more effectively extracted after treatment. Therefore, at the initial stage, individual flavonoid contents were boosted and a reduction correlated with polyphenol oxidase and peroxidase activities. Jujube pulp treated at 400 MPa showed no significant difference in total flavonid content than an untreated sample. However, total flavonoid content increased with increasing pressure (500 and 600 MPa) in jujube pulp. However, jujube pulp treated with high pressure also showed better retention of total flavonoid content as compared to thermal treatment (100°C for 10 min) during storage at 4 and 15°C (Shen et al., 2016). Distributed and aggregated flavonoid content within the fruit pulp might be the reason for improved flavonoid content after high pressure treatment (Shen et al., 2016). However, higher pressure yielded greater depletion of total flavonoid content than that under lower pressure, but pressure-treated samples had higher total flavonoid content than untreated samples in mango during 14 days of storage (Ortega et al., 2013).These authors stated that the synthesized flavonoids and enzymatic activity are mainly responsible for the changes inflavonoid contents. Contradictory results were obtained by Du (2016) who revealed that total flavonoid content in lemon juice degrades because quercetinase activity is elevated by high pressure. (−)-Epicatechin, rutin, and total flavonoid contents in litchi juice are significantly higher after treatment with high-pressure carbon dioxide as compared to control samples because of nonenzymatic oxidation (Liu et al., 2015). High-pressure processing and ultra-high-pressure processing have detrimental effects on total flavonoid content and quercetin aglycone concentration in mulberry juice in comparison with untreated samples (Yu et al., 2014; Wang et al., 2016).The control samples had higher proanthocyanidin content in cranberry juice than did high-pressure-treated samples during storage (Giacarini, 2008).The reduction correlates with oxidation of flavonoid compounds owing to increased polyphenol oxidase activity during processing. An increasing trend was observed in orange juice in terms of naringenin and hesperetin content in comparison with freshly squeezed juice (Sanchen-moreno et al., 2005). Similar results were obtained on different individual flavonoid contents in orange and tangerine juice (Begoña de et al., 2013) and prickly pear juice (Jiménez-Aguilar et al., 2015) in comparison with untreated samples. Structural changes might lead to increased flavonoid content in juice during high-pressure processing. However, high pressure decreases hesperidin and naringin contents in orange peel (M'hiri et al., 2015) and citrus sulcata fruit (Wang et al., 2011) owing to decomposition of flavones. However, high hydrostatic pressure extraction and agitation extraction do not produce significant differences in the rutin content of papaya (Uribe et al., 2015). However, hesperidin content is markedly increased whereas eriocitrin, eriodictyol, naringenin, hesperetin, kaempferol, and narirutin concentrations are decreased in orange juice after high-pressure processing (Estrada, 2011) because of cloud fraction may increase the hesperidin. Chauhan et al. (2011) reported that temperature is a more crucial factor than pressure and processing time. Moreover, pressure and processing time negatively affect total flavonoid content in black grape juice.

Monomers (+)-catechin and (−)-epicatechin are upregulated, whereas dimers of catechins and procyanidins are downregulated in apple cubes immersed in water after ultrasound treatment in comparison with untreated samples (Mieszczakowska-Frąc et al., 2016). This research group demonstrated that prolonged sonication, incubation without ultrasound, and immersion in sucrose solution reduceflavan-3-ol contents of apple cubes as compared to raw apple cubes. In this regard, changes in microstructure are one of the main reasons for the influenceonflavan-3-ols content in apple cubes. Various ultrasound treatment factors (solvent, temperature, ultrasound intensity, liquid height, pulse length, and duty cycle) were evaluated for extraction of different individual flavonoids from citrus fruit. Types of solvent and temperature were found to be the crucial factors for the degradation of flavonoid content rather than other factors. However, flavonoid degradation rate also depends on ultrasound intensity, pulse length, and duty cycle. Lengthened ultrasound duration also enhances the degradation of quercetin. Changes of flavonoid content may be associated with oxidation, polymerization, and decomposition

Table 3. Impact of nonthermal processing on flavonoids content of fruits.

Fruits	Product type	Processing conditions	Name of flavonoids	Impact on flavonoids content	References
Apple	Juice	High-pressure homogenization processing at 250 MPa for 10 min	Hesperidin, phloridzin, epigallocatechin gallate	↓Hesperidin, phloridzin, epigallocatechin gallate	He et al. (2016)
Orange	Juice	High-pressure homogenization processing at 250 MPa for 10 min	Naringin, hesperetin-rutinoside, naringenin-trisaccharide, luteolin-rutinoside, and quercetin-trisaccharide	↓Hesperetin-rutinoside	He et al. (2016)
Grape	Juice	High-pressure homogenization processing at 250 MPa for 10 min	Epicatechin, proanthocyanidin	↓Epicatechin	He et al. (2016)
Grape	Juice	Under different pressures (0.1, 120, 160, and 200 MPa), at different temperatures (15, 20, 37, 54 and 61°C).	Naringin	Depending on conditions	Ferreira el al. (2008)
Orange	Juice	Pressure 400 MPa for 1 min at 40°C	Naringenin, hesperetin	↓Naringenin, hesperetin	Plaza et al. (2011)
Orange	Juice	Pressure 100 MPa/60°C/5 min, 350 MPa/30°C/2.5 min, and 400 MPa/40°C/1 min	Naringenin, hesperetin	Higher pressure increased flavonoids content	Sánchez-Moreno et al. (2003)
Jujube	Pulp	Pressure 400, 500, and 600 MPa for 20 min at room temperature	Total flavonoid	Higher pressure increased flavonoids content	Shen et al. (2016)
Mango	Whole fruits	High pressure (15, 30, or 60 MPa for 10 or 20 min at 25°C)	Total flavonoid	Higher pressure decreased flavonoids content	Ortega, Ramirez et al. (2013)
Honey dew melon	Juice	High pressure (at 300, 400, 500, and 600 MPa, 20 and 60°C for 5 min)	Total flavonoid content	↓Total flavonoid content	Du (2016)
Litchi	Juice	High-pressure carbon dioxide (8 MPa, for 36°Cat 120 s)	(−)-Epicatechin, rutin and total flavonoid content	↑All flavonoids content	Liu et al. (2015)
Mulberry	juice	High pressure 500 MPa for 10 min	Total falvonoid	↓Total falvonoid	Wang et al. (2016)
Mulberry	juice	Ultra-high pressure homogenization (UHPH) processing at 200 MPa for 1—3 successive passes	Quercetin aglycone	↓Quercetin aglycone	Yu et al. (2014)
Cranberry	juice	High pressure (at 278 and 551 MPa, for 5 and 20 min)	Proanthocyanidins	↓Proanthocyanidins	Giacarini (2008)
Orange	Juice	High pressure (400 MPa for 1 min at 40°C)	Naringenin, hesperetin, total flavanones	↑All flavonoid contents	Sanchen-moreno et al. (2005)
Citrus (oranges, tangerines)	Juice	Whole peeled citrus fruit before juicing (200 MPa/25°C/1 min), on juice obtained from whole-pressurized citrus fruit (400 MPa/40°C/1 min), on freshly squeezed juices (400 MPa/40°C/1 min)	Hesperidin, narirutin, naringin-7-0-glucoside, apigenin-7, 8-di-glucoside, dydimin	↑All flavonoid contents	Begoña de et al. (2013)
Prickly pears	Juice	High pressure (at 400 or 550 MPa, at room temperature, for 0–16 min).	Quercetin, kaempferol, and isorhamnetin contents	↑All flavonoid contents	Jiménez-Aguilar et al. (2015)
Oange	Peel	High pressure (0.1, 50, and 100 MPa for 30 min at 35°C)	Total flavonoid and different individual flavonoid	↓Naringenin and hesperetin	M'hiri et al. (2015)
Citrus sulcata	Peel or edible fruit powder	High pressure (100 atmospheres for 30 min)	Naringenin, hesperetin, and total flavanones	↓All flavonoids content	Wang et al. (2011)
Papaya	Paste	High pressure at 500 MPa for 10 min	Rutin	↔Rutin	Uribe et al. (2015)
Orange	Juice	High pressure (100, 200, and 300 MPa)	Narirutin, hesperidin, eriocitrin, eriodictyol, naringenin, hesperetin, and kaempferol	↑ Hesperidin	Estrada (2011)
Black grape	Juice	High pressure (400–600 MPa), temperature (40–60°C), and processing time (2–4 min)	Total flavonoid	↓All flavonoids content	Chauhan et al. (2011)
Apple	Cubes	Sonicated at 40°C fitted with ultrasound transducers (25 kHz, 0.1 W/cm^3, 5-μm wave amplitude) at 30 rpm. Submerged in distilled water or 60 °Bx sucrose solution for 45 and 90 min with or without ultrasound application.	Monomers: (+)-catechin, (−)-epicatechin, dimers of catechins, Procyanidins.	↑ Monomers ↓ Dimers	Mieszczakowska-Frąc et al. (2016)
Citrus fruits	Whole fruits	Ultrasound intensity (10.19, 15.29, 15.80, 16.31, 20.89, 23.95 W/cm^2), liquid height (2, 4, 6, 8, 10, 12 cm), pulse length (0.2, 0.5, 1, 2, 4, 8 s), and duty cycle (33.3, 40, 50, 66.7, 100%), temperature (25, 5, 25, 45, and 65 μC) and solvent (methanol, 80% methanol, ethanol, 80% ethanol, water)	Eriocitrin, narirutin, neohesperidin, quercitrin, eridictyol, didymin, naringenin, luteolin, sinensetin, nobiletin, tangeretin, naringin, and hesperidin	Depending on conditions	Qiao et al. (2014)

↓, Decreased; ↑, increased; ↔, unchanged.

Table 4. Effect of nonthermal processing on flavonoids content of vegetables.

Vegetables	Product type	Processing conditions	Name of flavonoids	Impact on flavonoids content	References
Carrot and spinach	Carrot shredded into small pieces, spinach	100, 300, and 500 MPa for 20 min at 20°C using a high hydrostatic pressure	Total flavonoid contents	↑Total flavonoid contents	Jung et al. (2013)
Garlic	Pastes	High pressure processed at 200, 400, and 600 MPa pressures for a period of 15 min at 30°C	Total flavonoid contents	↑Total flavonoid contents	Unni et al. (2014)
Onions	Slices	High pressure processed at 100, 250, and 400 MPa pressures for a temperature 5, 27.5, and 50°C.	Total quercetin, quercetin-40 glucosid, quercetin-3,40-diglucoside	Depending on pressure and time.	Roldan-Marın et al. (2009)
Spinach	Powder	Ultrasound at frequency (37 and 80 KHz), temperature (30, 40, and 50°C) time (5, 10, 15, 20, 25, and 30 min) and power (30, 50, and 70%)	Total flavonoid contents	Depending on conditions	Altemimi et al. (2015)
Defatted hemp, flax seed, and while canola	Cake	Ultrasound with extraction time (20, 30, and 35 min) and temperatures (40, 50, 60, and 70°C), solvent volume (25, 50, 75, and 100 mL) at fixed power (200 W)	Total flavonoid contents	↑Total flavonoid contents (40 to 50°C) ↓Total flavonoid contents (60 to 70°C)	Sue-Siang and Birch (2014)
Pumkin	Powder	Ultrasound sonicator power level at 30, 50, and 70% duration of 10, 20, and 30 min at 30, 40, and 50°C	Myricetin	↑Myricetin content (lower exposure time) ↑↓Myricetin content (higher exposure time)	Altemimi et al. (2015)
Purple potato	Raw, baked, boiled	Ultrasound at sonication time (20, 50, and 80 min), frequency of 20 kHz, power level 5, 15, 25, and power 750 W	Quercetin	↑Quercetin content (lower exposure time) ↓Quercetin content (higher exposure time)	Damşa et al. (2016)
Chinese cabbage	Raw	Ultrasound at extraction time 20, 30, and 40 min frequency of 42 kHz and power 135 W, methanol: water (40:60, 60:40, 80:20) at 30°C	Quercetin	↑Quercetin content (lower exposure time) ↓Quercetin content (higher exposure time)	Kumar et al. (2014)
Soybeans	Powder	Ultrasound at 200 W and 24 kHz, 100% of nominal power, with EtOH, MeOH, or MeCN (between 30 and 70%), and two temperatures (10 and 60°C)	Daidzin, glycitin, genistin, and malonyl genistin	↑Isoflavone content (lower exposure time) ↓Isoflavone content (higher exposure time)	Rostagno et al. (2003)
Onion	Slices	Irradiated with 10 kJ/m^2 at 4°C (UV lamp, wavelength at 254 nm, 2 tubes at 4 W)	Flavonols: two major (quercetin 3,4-diglucoside (Q3,4dg) and quercetin 4-glucoside (Q4g)	↑All flavonoid content	Pérez-Gregorio et al. (2011)
Onion	slices	Treated with UV radiation	Quercetin	↑Quercetin	Higashio et al. (2005)
Barley	leaves	UV-B was provided by UVB-313 fluorescent sunlamps for 6 h each day	Saponarin and lutonarin	↑Saponarin and lutonarin	Liu et al. (1995)
Asparagus	Fresh	Average fluence rate of 8.2 Ws/m^2 at a mean distance of 30 cm) at dosages of either 0.54 kJ/m^2 (low = L) or 1.08 kJ/m^2 (medium = M) using a UV-B fluorescence light source	Quercetin-3,4′-O-diglucoside; quercetin-4′-O-monoglucoside	↑Quercetin	Eichholz et al. (2012)
Pepper	Fresh leaf	Ultraviolet radiation with UV lamps. UV-A (320-390 nm), UV-B (312 nm), and UV-C (254 nm) irradiation with a density of 6.1 (W/m^2), 5.8 (W/m^2) and 5.7 (W/m^2), respectively, 27 min per day for 14 days	Rutin and quercetin	↑Rutin and quercetin	Mahdavian et al. (2008)

↓, Decreased; ↑, increased; ↔, unchanged.

(Qiao et al., 2014). Total flavonoid content of grape peel, plum peel, and different figs and individual flavonoid contents in orange juice were markedly increased after ultrasound extraction in comparison with control (Jokić et al., 2014; Medina-Meza and Barbosa-Cánovas, 2015; M'hiri et al., 2015). A similar increasing trend was observed for naringin and hesperidin in orange peel (Khan et al., 2010) and total flavonoid content was increased in Pyracantha fortuneana fruit powder (Zhang et al., 2014) by ultrasound extraction. Medina-Meza et al. (2016) also showed ultrasound could enhance the quercetin content in raspberry and bluberry puree as compared to raw puree. Disruption of cell wall by ultrasound may promote the release of

floavonoid compounds; thus, total and individual flavonoid contents are increased. The total flavonoid content is lower in *citrus sulcata* peel after extraction with ultrasound than after Soxhlet extraction because the extraction parameters were different (Wang et al., 2011). However, drying at 30°C without ultrasound causesa greater loss of flavonoids in apple slices as compared to drying at 30°C with ultrasound treatment, although the values were not significantly different. However, a high-drying temperature with ultrasound treatment yields a greater loss in flavonoids than does drying at lower temperature without ultrasound treatment (Rodríguez et al., 2014). This research group revealed that flavonoid loss was related to temperature and microstructure. Ouahida et al. (2016) showed higher total flavonoid content and lower tannin content in phoenix dactylifera after extraction with ultrasound than after extraction with agitation. However, total flavonoid content in pear juice and flavonoids and flavonols content in apple juice increases with the increasing sonication duration (Abid et al., 2013; Saeeduddin et al., 2016). However, longer sonication duration reduces the rutin and quercetin contents in peach. The amount of rutin and quercetin quickly increases in peach from 30 to 41°C; after that, rutin content declines with increasing temperature (Altemimi et al., 2015). Rutin content in papaya is not significantly different between samples processed by ultrasound and agitation extraction (Uribe et al., 2015). Hesperidin content of penggan peel depends on ultrasonication time, temperature, and power (Ma et al., 2008). Higher temperature can enhance the flavonoid content because of increased solubility of the solute; subsequently, higher temperature also reduces the flavonoid content because of a reduction in the solvent density (Altemimi et al., 2015). Total flavonoid content decreases in apple slices owing to longer ultrasound treatment before air drying (OpalIć et al., 2009). Prolonged sonication may cause oxidation of flavonoid content. Chukwumah et al. (2009) revealed that multi frequency processing can be more efficient at extracting biochanin A, daidzein, genistein, and trans-resveratrol from peanuts than a single-frequency treatment can. Cavitation and interaction with other compounds might be the reason for increased flavonoid content. Formation of cavitation, changes in the position of a structure, and disruption of microstructure could affect flavonoid content during ultrasound processing.

Pulsed electric field-treated and untreated samples of grape juice do not show sufficient differences in catechin content (Marsellés-Fontanet et al., 2013). However, hesperidin, rutin, narirutin, and quercetin contents in fruit juice beverage are higher after treatment with pulse electric field than untreated samples. Moreover hesperidin, rutin, narirutin, and quercetin contents are not detected in control samples after 21 days of storage. However, hesperidin content is increased, whereas rutin, narirutin, and quercetin content decrease in a fruit juice beverage processed with pulsed electric field during storage (Morales-delapena et al., 2016). Pulsed electric field yields higher concentrations of total flavanones (naringenin and hesperetin) in orange juice as compared to untreated samples, although the values are not significantly different (Sanchen-moreno et al., 2005). However, a significant difference in isorhamnetin-3-O-rutinoside content was found in cactus fruit juice, and total flavonoid content in grape and plum peels between the pulsed electric field and control sample (Medina-Meza and Barbosa-Cánovas, 2015; Moussa-Ayoub et al., 2016). Freshly squeezed orange juice contains higher concentration of total flavanones (naringenin, hesperetin) in comparison with samples treated with pulsed electric field during refrigerated storage at 4°C (Plaza et al., 2011). Quercetin content is significantly higher in raspberry and blueberry puree than raw puree after treated with pulse electric field (Medina-Meza et al., 2016) Kaempferol, quercetin, and myricetin contents in strawberry juice are not significantly different between a pulsed electric field-processed sample and untreated sample on day 1 (Odriozola-Serrano et al., 2008). Later, this research group showed that the control sample did not have any individual flavonoid content after 21 days of storage; myricetin was not detected in treated samples after 28 days of storage at 4°C. However, hesperidin, rutin, narirutin, quercetin, and apigenin content of fruit juice-soya milk treated with pulse electric field is significantly different from that of the control, and the control also did not show any flavonoid content after 14 days of storage at 4°C (Morales-delaPeña et al., 2011). Just after processing, total aglycone and total glucoside content of fruit juice-soymilk beverage is not significantly different between untreated samples and samples treated with pulsed electric field. Nevertheless, the treated sample showed an increasing trend relative to control during storage at 4°C (Morales-delaPeña et al., 2010). Naringin, neohesperidin, hesperidin, kamferol, luteolin, apijenin, rutin, isoquercetin, quercetin, neoeriocitrin, eriocitrin, and naringenin contents in orange juice depend on pulsed electric field parameters throughout the storage period (Agcam et al., 2014). However, naringin and hesperidin content in orange peels increases with increasing electric field strength (Luengo et al., 2013). Moreover, catechin, epicatechin, and rutin content in grape paste also increases after treatment with pulsed electric field (López-Giral, 2015). Pulsed electric field and a control sample were insignificantly different in terms of (+)-catechin, (−)-epicatechin, uercetin 3-O-galactoside, quercetin 3-O-glucoside, quercetin 3-O-rhamnoside, quercetin 3-O-rutinoside, procyanidin B1, procyanidin B2, phloretin, phloridzin-dihydrate, and phloretin in apple mash (Schilling et al., 2007).

There are many reasons for the changes in flavonoid contents during treatment with pulsed electric field (Rao, 2012). Some are given below: (i) Formation of new compounds because of biochemical reactions during pulsed electric field treatment. (ii) Cell membrane rupture can be promoted by pulsed electric field; hence, a release of free flavonoids. (iii) PPO inactivation could also prevent the loss of flavonoid content during pulsed electric field treatment as well as increase PAL activity, thus improving the concentrations of flavonoids.

Freshly cut honey pineapple, banana, and guava were exposed to ultraviolet light C (UV-C) for 0, 10, 20, or 30 min as reported by Alothman et al. (2009). They found that flavonoid content of guava and banana increased significantly with the increasing treatment duration, but flavonoid content increased significantly after 10 min of treatment of honey pineapple. The flavonoid content in blueberries (Wang et al., 2009), red raspberries (Wang et al., 2009), yellow bell pepper fruit (Promyou and Supapvanich, 2012), and black currant fruit (Huyskens-Keil et al., 2007) increased after UV-C illumination. The investigators stated that the synthesis of phenolic compounds in the

presence of a phenylalanine ammonialyase activity as well as promotion of the extractability could be the reason for increased flavonoid content during UV treatment. However, contradictory results were obtained in pineapple juice after UV treatment relative to the control (Goh et al., 2012). Catechin, epicatechin, procyanidin B2, quercetin 3-galactoside, and quercetin 3-rhamnoside concentrations increased with the increasing UV-C dose, but procyanidin B_1 concentration decreased in grapes after UV-C irradiation (Hemmaty et al., 2011). Naringenin content in vine-ripe tomatoes decreases with an increase in the UV-C irradiation duration, while rutin content in vine-ripe tomatoes dependents on the dose of UV-C irradiation (Bravo et al., 2013). UV-treated peach fruits showed higher amounts of individual and total flavonol glycosides than the control did (Scattino et al., 2014). This research also revealed that UV-B irradiation has zero or even negative impact on individual and total flavonol glycosides of big top nectar fruit. Furthermore, flavonoid and flavonol concentration increased by 21% in tomato peels after treatment with UV-B radiation. UV may promote accumulation of the flavonoids because of DNA damage, and UV also promotes formation of free radicals and reactive oxygen species, there by influencing flavonoid content (Hemmaty et al., 2011; Bravo et al., 2013). On the other hand, flavonoid and flavonol concentrations increased by 27% and 48%, respectively, in tomatoe flesh after treatment with UV-B radiation (Castagna et al., 2014). A lower exposure time of UV-C irradiation of mango juice sample yielded a 3% increase, whereas a higher exposure time decreased the total flavonoid content when compared to control (Santhirasegaram et al., 2015). UV irradiation does not affect the flavonol content in grape skin, but UV radiation could enhance the resveratrol glucoside content of grapes during storage (Cantos et al., 2010). An increasing trend was observed for flavonoid content in tomatoes after UV-irradiation (Calvenzani et al., 2001). Formation of free radicals by UV may enhance flavonoid content, whereas longer UV exposure might suppress flavonoid content (Santhirasegaram et al., 2015). Some authors mentioned that phenylpropanoid compounds and biosynthetic genes are upregulated by UV irradiation and thus stimulate the flavonoid content (Calvenzani et al., 2001; Cantos et al., 2010). The phenolic biosynthesis pathway maybe stimulated because of activation of the phenylalanine ammonia lyase enzyme (and polyphenol oxidase could be inactivated after UV exposure) thus affecting flavonoid content (Santhirasegaram et al., 2015).

Impact of nonthermal processing on flavonoid content in vegetables

Carrot and spinach treated under high pressure are reported to show higher total flavonoids content than the control group (Jung et al., 2013). A positive correlation was observed between total flavonoid content and pressure level. Jung et al. (2013) demonstrated pressure-induced cell rupture, which may enhance flavonoid extraction. A similar increase in total flavonoid content was observed in high-pressure processing of onions (Unni et al., 2014). Pressure and temperature are crucial factors for the extraction of flavonols from onions (Roldan-Marın et al., 2009). In comparison to untreated onions, those treated at low temperature (5°C) and high pressure (100 and 400 MPa) showed up regulated levels of quercetin-3,4′-diglucoside(82.75%), quercetin-4′-glucoside (12.90%), and free quercetin (4.35%) (Roldan-Marın et al., 2009) attributable to changes in quercetin structure under the influence of pressure and temperature.

Ultrasonic frequency, temperature, time, and power levels may affect flavonoid content in spinach (Altemimi et al., 2015). Low extraction temperature and ultrasonic power are the most important factors for the extraction of flavonoids from spinach. Flavonoid content in spinach increases with increasing power levels during ultrasonic processing. Ultrasonic temperature exerts as significant effect on flavonoid content in defatted hemp, flax seed, and canola. Total flavonoid content increases at 40–50°C; at higher temperatures, flavonoid content in seeds decreases. However, extraction period is reported to influence the flavonoid content (Sue-Siang and Birch, 2014). Ultrasonic extraction temperature and time are vital factors for the extraction of myricetin from pumpkin (Altemimi et al., 2015). Longer ultrasonic extraction time decreases the flavonoid content in purple potato (Damşa et al., 2016). Similar results were reported for quercetin extraction from cabbage (Kumar et al., 2014). In soybean, higher ultrasonic extraction temperature yields higher isoflavone content, whereas longer extraction time reduces isoflavone yield (Rostagno et al., 2003). The cell membrane may degrade due to cavitation during ultrasonication, there by contributing to flavonoid extraction (Altemimi et al., 2015). As the number of cavitation bubble depends on temperature, higher ultrasonic temperature may enhance cavitation by cell rupture; however, ultrasound frequency and power may decrease the flavonoid content via oxidation (Sue-Siang and Birch, 2014).

Pérez-Gregorio et al. (2011) reported that onion slices treated with ultraviolet (UV)-C radiation showed 35% more flavonol than the control group and that quercetin diglucosides levels were much higher than those of glucosides. Similar results were demonstrated for quercetin content in onion slices by Higashio et al. (2005) and saponarin and lutonarin content in barley by Liu et al. (1995). Quercetin-3,4′-O-diglucoside and quercetin-4′-O-monoglucoside in asparagus are markedly up regulated following treatment with different sources of UV-B (Eichholz et al., 2012). Mahdavian et al. (2008) reported increasing levels of rutin and quercetin in pepper leaves after treatment with different sources of UV light and showed that UV-C treatment yielded more rutin and quercetin than UV-A and UV-B. UV irradiation may reduce the oxidative stress and activate phenylpropanoid metabolism, thereby increasing the flavonoid content (Higashio et al., 2005; Pérez-Gregorio et al., 2011).

Stability of the flavonoid content during thermal and nonthermal processing

Flavonoids have hydroxyl and ketone groups, and unsaturated double bonds are responsible for the stability (Qiao et al., 2014). The position of the hydroxyl group, sugar molecules, and microstructure are also crucial factors for stability and for retention of the flavonoids content during processing (Biesaga, 2011). Buchner et al. (2006) mentioned that pH and reaction duration influence quercetin and rutin contents in the presence

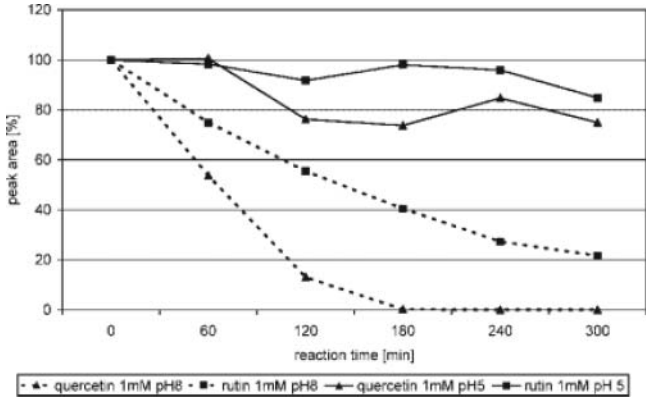

Figure 9. Degradation of quercetin and rutin in an aqueous solution at 100°C with air perfusion at different pH values (adapted from Buchner et al., 2006).

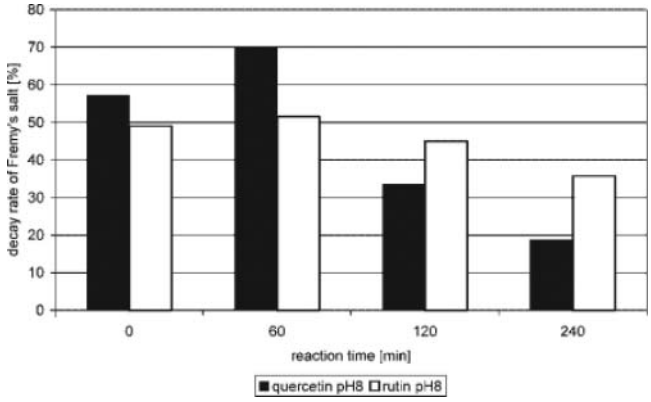

Figure 11. Electron spin resonance (ESR) analysis of rutin and quercetin degradation samples (Fremy's salt, incubation for 20 min) (adapted from Buchner et al., 2006).

or absence of oxygen. Quercetin and rutin content decreased by almost 75% after 300 min at pH 5. Quercetin was not detectable by HPLC/DAD after 300 min whereas changes in rutin were not significant between the concentration and interval under weak basic reaction at pH 8 (Fig. 9).

Rutin also shows higher resistance to oxidation than quercetin does (Fig. 10) because the sugar moiety could work as a barrier the 3-hydroxyl group in the C-ring (Buchner et al., 2006). Rutin also showed higher stability than quercetin did because of higher radical scavenging (Fig. 11). Flavonol is also capable of replacing the one or two hydrogen atoms and forms the quinonoid structures during the reaction in the presence of the solvent, light, oxygen, and so on (Buchner et al., 2006). Fig. 12 shows the pathway of degradation of quercetin. First, quercetin is form protocatechuic acid and then produces of 2-(3′,4′-dihydroxyphenyl)-2,3-dihydroxy-prop-2-en-1-al in the presence of oxygen but still nucleophilic form of quercetin are appear. Thus, the quinoic structure is formed because of oxidation of the quercetin in the presence of solvent molecules. Fragmentation of quercetin in the model system as examined by HPLC/DAD/ESI-MS^n is shown in Fig. 13 (Buchner et al., 2006) in aqueous solution (pH 8) at 100°C. There are various compound produced during fragmentation. Suggested compounds for *m/z* 195 *m/z* 177 is 2,3-dihydroxy-(3′,4′-dihydroxyphenyl)-prop-2-en-1-al. For *m/z* 153 *m/z* 108 is protocatechuic acid. For *m/z* 337 is 2, 5, 7, 3′, 4′-pentahydroxy-3, 4-flavandione. For *m/z* 211, *m/z* 179 *m/z* 151 is 2,2,5,7-tetrahydroxybenzofuran-3-on. For *m/z* 349, *m/z* 331 *m/z* 299, *m/z* 271 is 2-(3′, 4′-dihydroxyphenyl)-3,3,5,7-tetrahydroxy-2-methoxy-2,3-dihydrochromen-4-on. For *m/z* 347, *m/z* 315 *m/z* 211 is 2-(3′-methoxy-4-hydroxyphenyl)-3,5,7-trihydroxy-3-methoxy-2, 3-dihydrochromene-4-on-4-on. Rohn et al. (2007) demonstrated that above 180°C and over 60 min, flavonol in roasting onion undergoes rapid breakdown (Fig. 14). They also mentioned that the sugar moiety is rapidly degraded in the flavonol and results indifferent compounds (Fig. 15). Roasting temperature and time in the presence or absence of air also degrade squercetin-3,4′,-*O*-diglucoside in onion (Fig. 16). Qiao et al. (2014) found that quercetin stability is lower than that of the other 14 flavonoids during ultrasound processing. They also stated that oxidation, addition, polymerization, and decomposition reactions take place during ultrasound processing and yield various patterns of fragmentation of quercetin (Fig. 17). Changes in the structures are also important for keeping the flavonoid content during processing. Jung et al. (2013) observed cracks and many holes in carrots treated with high pressure, whereas swollen and agglomerated structure is observed in spinach treated with high pressure in comparison with untreated spinach (Fig. 18). Ultrasound application causes more shrinkage, cell collapse, fracturing, and disruption in apple tissue in comparison with samples without ultrasound treatment (Rodríguez et al., 2014) (Fig. 19). More disruption occurs in albedo cells in orange peel (Fig. 12) after treatment with ultrasound (Garcia-Perez et al., 2012). Carrots treated with pressure show separated and loosened structure as compared to fresh samples (Nguyen et al., 2007) (Fig. 20). Therefore, it can be concluded that flavonoid structure and microstructure are responsible for stability and retention of flavonoid content during processing.

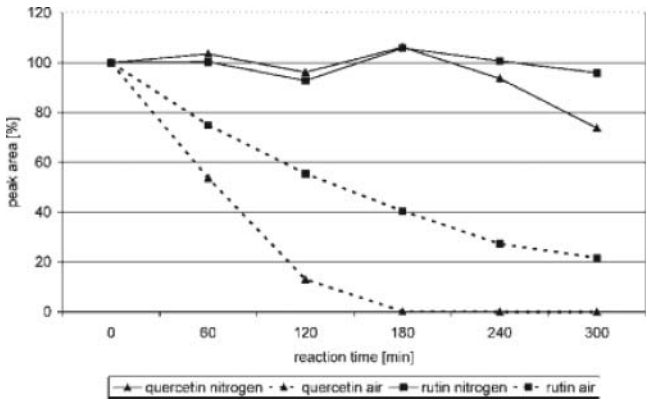

Figure 10. Degradation of quercetin and rutin in an aqueous solution (pH 8) at 100°C: a comparison between air and nitrogen perfusion (adapted from Buchner et al., 2006).

Bioavailability of flavonoid in fruits and vegetables

Bioavailability is the amount or portion of the absorbed substance that reaches the plasma in an unchanged form through a particular route (Ververidis et al., 2007). Improved absorption and formation of active metabolites in vivo is the main phenomenon for the bioavailability of flavonoids (Manach et al.,

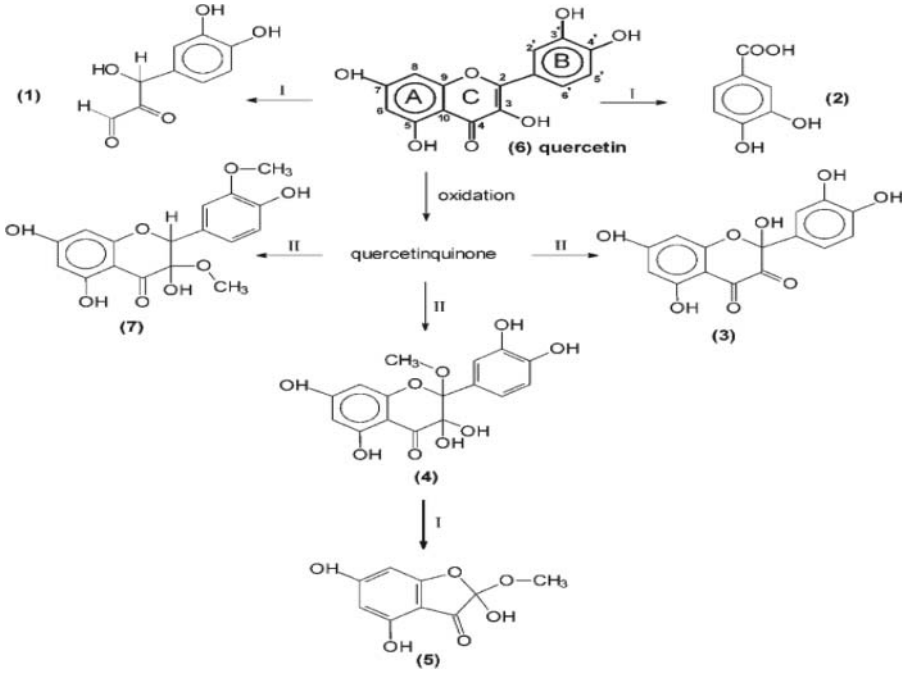

Figure 12. The oxidative reaction pathway for degradation of quercetin; I, cleavage; II, addition of nucleophiles (adapted from Buchner et al., 2006).

2005). Parameters usually considered for calculating the bioavailability of flavonoid include maximal plasma concentration (C_{max}), time to reach C_{max}, area under the plasma concentration–time curve, elimination half-life, and relative urinary excretion (Manach et al., 2005). Few studies have reported on the bioavailability of flavonoids after novel processing techniques. Table 5 shows the bioavailability of flavonoids after consumption of fruits and vegetables in liquid, solid, or processed forms. Most studies have been directed toward the bioavailability of flavonoids such quercetin, catechins, procyanidins, and isoflavones. Manach et al. (2005) reported that quercetin bioavailability varies with food source and glycoside type. Following consumption of orange, the concentration of hesperetin and naringenin was shown to be dose dependent in the plasma but not in the urinary excretion. The bioavailability of onion quercetins was found to be higher than that of apple and tea quercetins, owing to different types of glycosides (Hollman et al., 1995, 1997; Aziz et al., 1998; McAnlis et al., 1999;

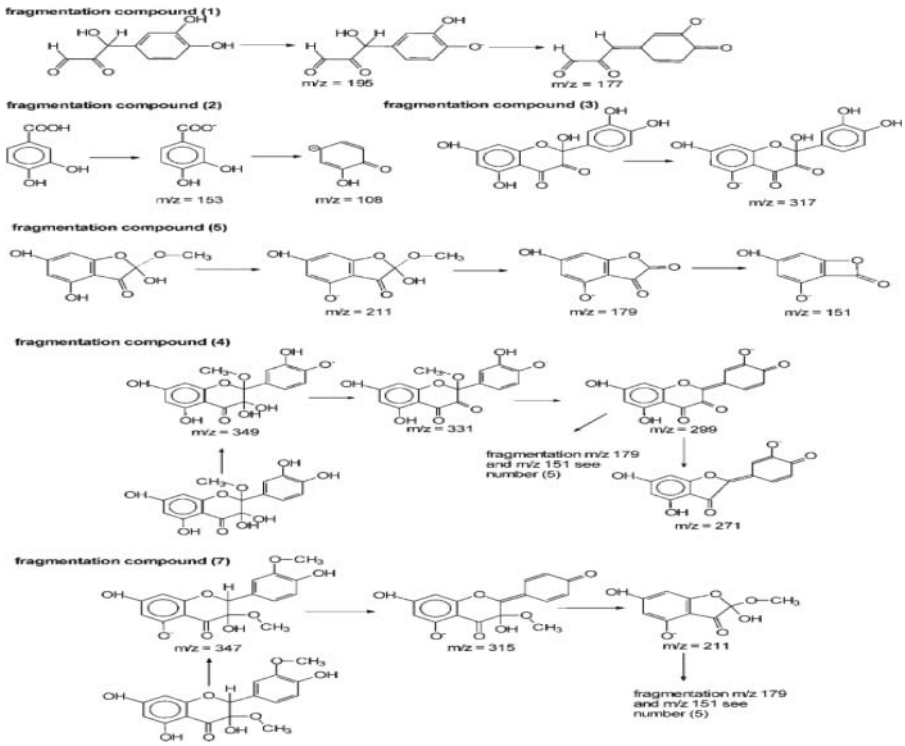

Figure 13. The fragmentation scheme of quercetin degradation products (adapted from Buchner et al., 2006).

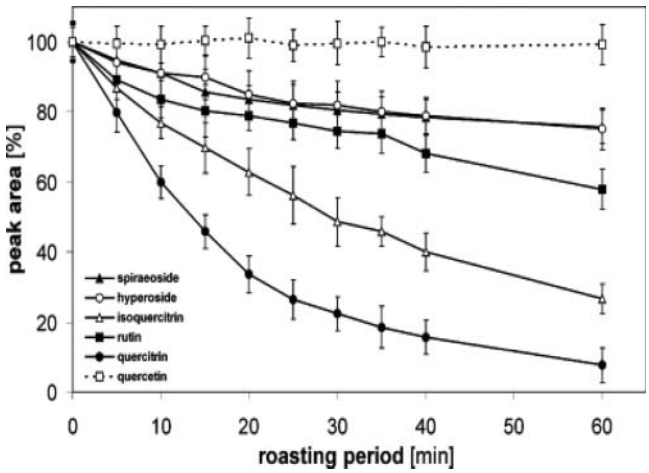

Figure 14. Degradation of selected quercetin glycosides under roasting conditions (dry roasting at 180°C) (adapted from Rohn et al., 2007).

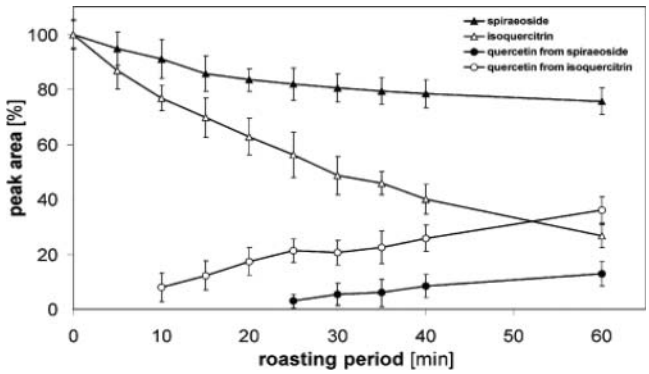

Figure 15. Formation of quercetin resulting from the degradation of spiraeoside and isoquercitrin (adapted from Rohn et al., 2007).

Graefe et al., 2001; DuPont et al., 2002). In comparison to quercetin capsules, quercetin-enriched cereal bars increased the concentration of isorhamnetin and tamarixetin in human plasma by four and nine times, respectively, due to food matrix. However, no significant difference in time-to-peak concentration (T_{max}) was observed between quercetin-enriched cereal and quercetin capsules (Egert et al., 2012). The C_{max} value of naringenin in cooked cherry tomatoes (0.06 ± 0.02 μmol/L) was reached at 2 h (T_{max}), whereas no naringenin peak was detected after ingestion of fresh cherry tomatoes (Bugianesi et al., 2004). Martínez-Huélamo et al. (2015) reported that the manufacturing process of tomato products (oil-free tomato sauce and tomato sauce enriched with refined olive oil) induces the release of more compounds from food matrix than in raw tomatoes, thereby improving the bioavailability in vivo. This may be attributed to thermal treatment, which may improve the bioavailability of processed tomatoes. The plasma concentration, time to reach plasma concentration, area under the plasma concentration–time curve, and relative urinary excretion of naringenin and hesperetin were different after consumption of tomato paste (Bugianesi et al., 2002), grape juice (Erlund et al., 2001), and orange juice (Erlund et al., 2001), owing to differences in doses and absorption routes. Henning et al. (2004) reported that C_{max}, area under the curve, and T_{max} values significantly increased for flavonoids (epigallocatechin, epicatechin, epigallocatechin gallate, and epicatechin gallate) in green tea supplement than those in green tea and black tea. The bioavailability of flavonoids was reported to increase for green tea supplement in capsule form. In addition, the bioavailability of isoflavones varied with the type and dose of soybean products (Xu et al., 1994; Watanabe et al., 1998; Shelnutt et al., 2000; Xu et al., 2000). Zubik and Meydani (2003) found no significant differences in the bioavailability of isoflavones (genistein and daidzein) from aglycone and glucoside forms of soybean in American women. However, Setchell et al. (2001) reported that isoflavone bioavailability from glucoside was higher than that from aglycone, as the glucoside moiety displays an ability to protect the degradation of isoflavone structure. It was also shown that the plasma concentration of isoflavones may vary with the type of supplement ingested. Another study by Seeram et al. (2008) revealed similar absorption level of ellagic acid after consumption of pomegranate juice, pomegranate polyphenol liquid extract, and pomegranate polyphenol powder extract, although the absorption time was dependent on the polyphenol source. Ellagitannins are converted to ellagic acid in the small intestine. Quercetin concentration in plasma and urinary excretion was reported to increase after consumption of berries such as bilberries, lingonberries, blackcurrants, chokeberries, and small amounts of red raspberries and strawberries (Koli et al., 2010). Bansode et al. (2014) showed that C_{max} of procyanidin A2 was reached at 30 min and procyanidin A2 disappeared within 1 h of ingestion. These authors also reported C_{max} of catechin and epicatechin to be 90 min. Sano et al. (2003) found the plasma concentration of procyanidin B1 to be 0.011 μmol/L at 2 h. Taken together, bioavailability depends upon various factors such as molecular weight, glycosylation, metabolic conversion, interaction with colonic microflora (Thilakarathna and

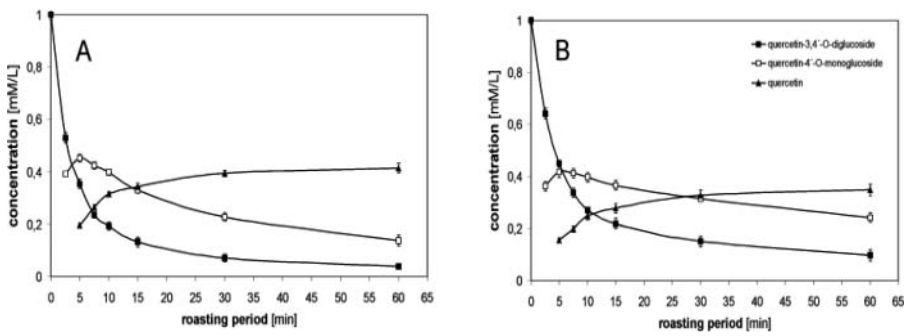

Figure 16. Degradation of quercetin-3,4′-O-diglucoside. (**a**) Roasting with free exposure to air and (b) roasting in a nitrogen atmosphere (adapted from Rohn et al., 2007).

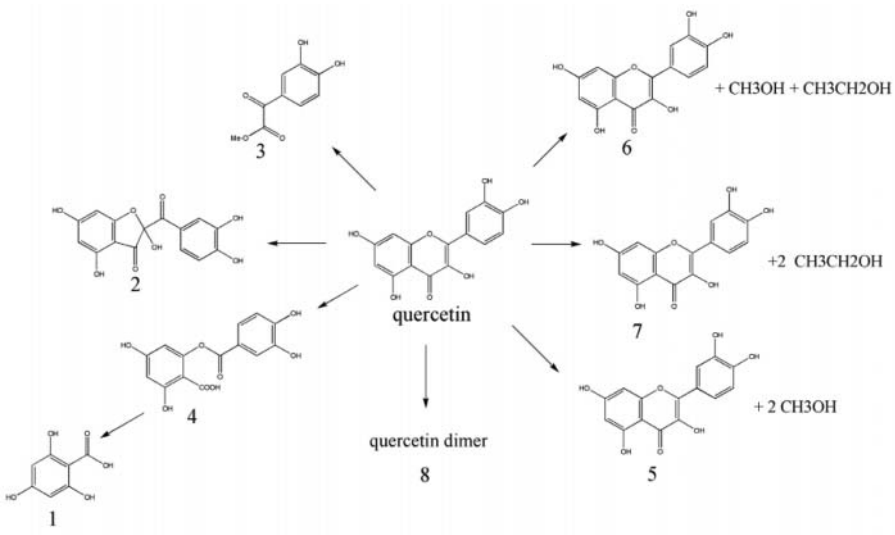

Figure 17. The proposed mechanism of degradation of quercetin under the influence of ultrasound treatment (adapted from Qiao et al., 2014).

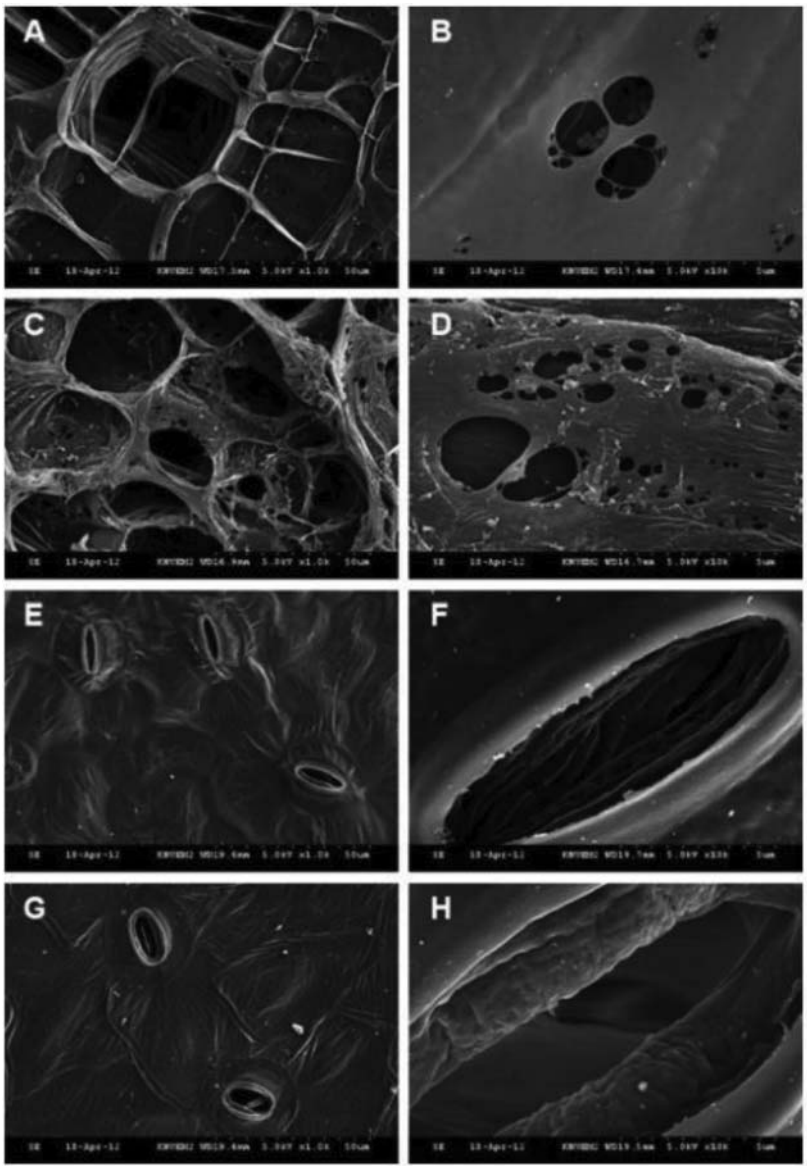

Figure 18. Scanning electron microscopy images. (a) Untreated carrot (control; × 1,000), (b) untreated carrot (control, × 10,000), (c) treated carrot (500 MPa, 20 min; × 1,000), (d) treated carrot (500 MPa, 20 min; × 10,000), (e) untreated spinach (control; × 1,000), (f) untreated spinach (control, × 10,000), (G) treated spinach (500 MPa, 20 min; × 1,000), (H) treated spinach (500 MPa, 20 min; × 10,000) (adapted from Jung et al., 2013).

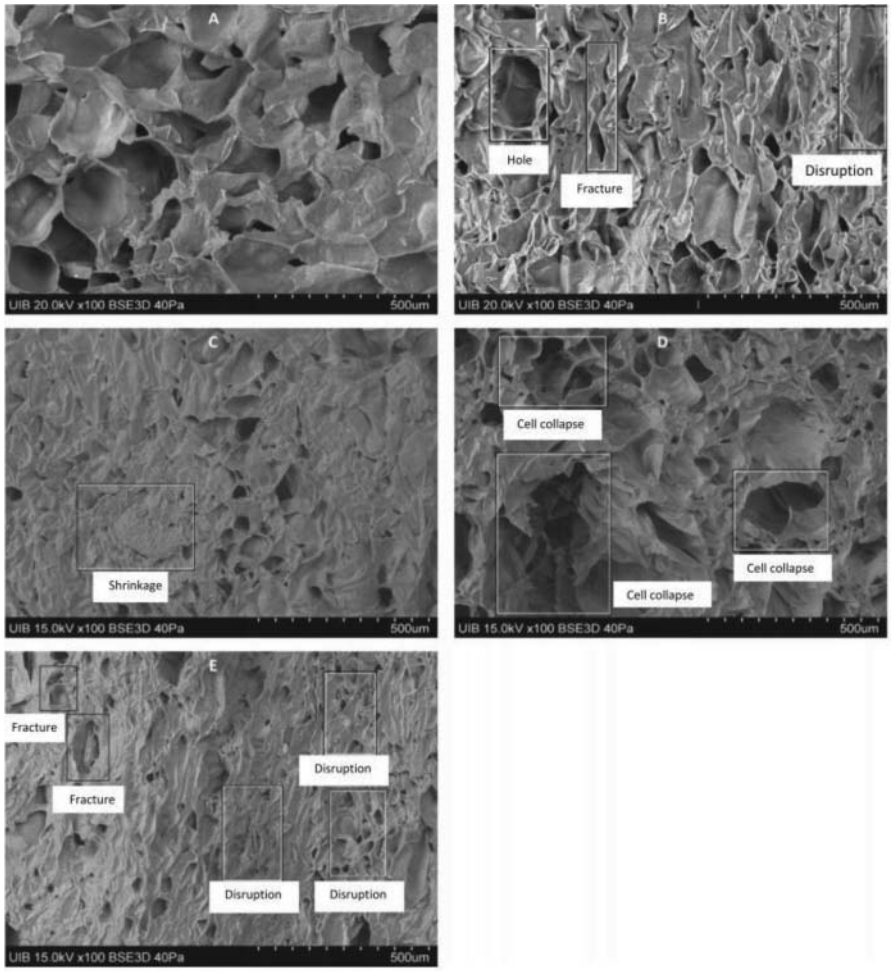

Figure 19. Effects of power ultrasound on apple tissue microstructure. Scanning electron micrographs of apple tissues. Fresh (not dried) (a), samples dried at 30°C without ultrasound (b), samples dried at 30°C (with 18.5 ± 0.9 kW/m^3 ultrasound) (c), samples dried at 70°C without ultrasound (d), samples dried at 70°C (with 30.8 ± 0.9 kW/m^3 ultrasound) (e) (adapted from Rodríguez et al., 2014).

Rupasinghe, 2013), ethnic background, dietary habit, intestinal microflora, food matrix, and administered dose (Zubik and Meydani, 2003).

Cytotoxicity of flavonoids from fruits and vegetables

Cytotoxicity of flavonoids has been reported at relatively higher doses (micromolar concentration range) (Sak, 2014). It is impossible to achieve higher plasma flavonoid concentrations by oral administration. However, intravenous injection and regular intake of flavonoids for a long time may result in higher levels of flavonoids in plasma (Sak, 2014). Cytotoxicity may also be related to flavonoids structure, cancer type, and differences in the sensitivity and selectivity of tumor cells (Sak, 2014). Cytotoxicity of flavonoids from various fruits and vegetables is shown in Table 6. Cytotoxic effect of tomatoes was observed against human cancer cells and renal cancer cells after thermal processing (10 min at 92°C), owing to an increase in the levels of certain flavonoids. Quercetin3-β-D-glucoside has been shown to exert antiproliferative activity on different cell lines. In addition, higher naringenin level may enhance the cytotoxic effect against cell lines. Nonprocessed tomato extract, however, showed positive effect on cell growth, attributable to the lower levels of flavonoids (Raiola et al., 2016). Cocoa beans processed using different techniques (roasted, roasted well-fermented, and unroasted well-fermented) may inhibit cell proliferation, modify cell cycle, and increase apoptosis in human lungcarcinoma cells due to the presence of flavonols and procyanidins (Bauer et al., 2016). Processed mango kernels exhibit lower cytotoxicity as compared with the control (potassium dichromate), as measured by in vitro lethality assay, which may be attributable to its flavonoid contents (Arogba, 2014). Similar results were reported by Anilakumar et al. (2003), wherein long-term consumption of processed mango induced cytotoxicity in rats owing to the presence of antioxidants. Cho et al. (2016) revealed that onion extract may display protective effect against cytotoxicity and genotoxicity in human lymphocytes treated with bleomycin by reducing levels of reactive oxygen species and repairing DNA damage. Votto et al. (2010) showed that quercetin from onion extract exerts cytotoxic effect in tumoral cells. In addition, the ethanol extract of onion peel displays cytotoxic activity in HT-29 human colon carcinoma cells (Kim et al., 2013). Ovarian cancer may be suppressed by the consumption of soy and isoflavone (Zhang et al., 2004). Soybean phytoestrogens may act as anti-estrogenic agents and suppress

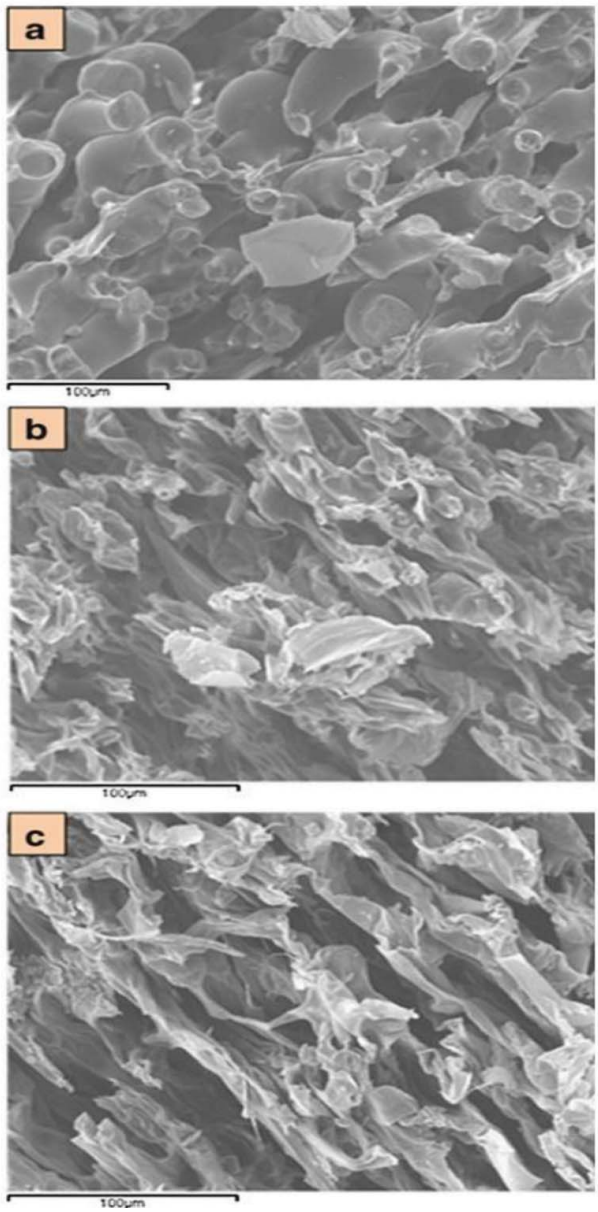

Figure 20. Cryo-SEM micrographs of albedo cells from orange peel. (a) Fresh (×350); (b) air dried (×500); (c) ultrasound-assisted drying (air dried + ultrasound with 90W × 500) (adapted from Garcia-Perez et al., 2012).

the growth and proliferation of ovarian cancer. Cranberry fruit exhibited cytotoxic effect in human ovarian, neuroblastoma, and prostate cancer cell lines but not lung fibroblast cells due to the presence of A-type proanthocyanidins with one to four linkages between two and eight epicatechin units (Singh et al., 2009). Gabiroba, murici, and the pulp of guapeva fruit extract showed inhibitory activity against HepG2 cells, owing to the presence of various flavonoids with antiproliferative properties (Malta et al., 2013). Dusman et al. (2014) reported that grape juices, both untreated and treated with UV irradiation, showed cytotoxicity and mutagenicity in HTC cells. Flavonoid compound from *Capsicum annum L.* seeds showed no cytotoxic effect in human red blood cells (Al-Fartosy and Zearah, 2013). Tannins and other flavonoids from ethanolic leaf extracts of various Thai vegetables such as *Barringtonia acutangula, Cratoxylumformosum, Limnophila aromatica, Polygonum odoratum, Syzygium gratum*, and *Schinus terebinthifolius* exhibited cytotoxic activity against different cell lines (Woraratphoka et al., 2012).

Transformations of flavonoids

Absorption and transformation of flavonoids is based on their glycoside or aglycone form. Under normal conditions, aglycones are absorbed in the small intestine, whereas glycosides are converted to aglycones by an intestinal enzyme or colonic microflora (Pandey and Rizvi, 2009; Kumar and Pandey, 2013). Aglycones and glycosides are transported into enterocytes through passive diffusion and sodium-glucose-linked transporter, respectively. Various absorption and transformation pathways of flavonoids are shown in Fig. 21. Very few studies have focused on transformation of flavonoids after thermal and nonthermal processing of fruits and vegetables. Soler et al. (2010) showed that luteolin from olive oil was converted into glucuronide and methyl-glucuronide conjugates in Caco-2/Tc7 cells through transport by apical, cellular, and basolateral compartments. Using Caco-2 cells, Brand et al. (2008) reported that citrus flavonoid hesperetin was metabolized into hesperetin 7-*O*-glucuronide and hesperetin 7-*O*-sulfate, which were transported to the apical side, whereas aglycone of hesperidin was found in the unconjugated form at the basolateral side. How-

Table 5. Bioavailability of flavonoid-containing foods.

Source	Dose	T_{max} plasma (h)	Plasma concentration (μmol/L)	Area under the curve (μmol·h/L)	Urinary excretion (% of intake)	Elimination half-life (h)	References
Orange juice	110 or 220 mg eq hesperetin	5.4–5.8	0.46–1.28	4.19–9.28	4.1–6.4	—	Manach et al. (2003)
Orange juice	22.6 or 45 mg eq naringenin	4.6–5	0.06–0.2	0.43–1.29	7.1–7.8	—	Manach et al. (2003)
Onions	89 mg quercetin eq	—	—	—	0.31	—	Hollman et al. (1995)
Onions	68 mg quercetin eq	0.7	0.74	7.7	—	28.0	Hollman et al. (1997)
Onions	186 mg quercetin eq	1.3-1.9	2.18	—	1.11	—	Aziz et al. (1998)
Onions	50 mg quercetin eq	2	0.83	—	—	—	McAnlis et al. (1999)
Onions	100 mg quercetin eq	0.68	7.6	32.1	6.4	10.9	Graefe et al. (2001)
Fried onions	64 mg quercetin eq	2.9	0.65	—	—	16.8	Hollman et al. (1996)
Apples	107 mg quercetin eq	2.5	0.3	3.5	—	23.0	Hollman et al. (1997)
Apple cider	1.6 mg quercetin eq	0.66–1	0.14	—	—	—	DuPont et al. (2002)
Buckwheat tea	200 mg quercetin eq	4.3	2.1	12.6	1.0	10.3	Graefe et al. (2001)

EGCG, epigallocatechin-3-gallate; EGC, epigallocatechin; ECG, epicatechin-3-gallate; EC, epicatechin; Da, daidzein; Ge, genistein; bw, body weight.

Table 6. Cytotoxic effects of flavonoid-containing foods.

Fruits/vegetables	Cell line	Cytotoxic activity	Assay method/time	References
Fresh and processed yellow tomatoes	HepG2, HEK293, and HeLa	Antiproliferative activity on different cell, cell growth inhibition	MTT assay/48 h Trypan blue dye exclusion assay/48 h	Raiola et al. (2016)
Cocoa beans (roasted, roasted well fermented, and unroasted well fermented)	A549	Cell viability depended on concentrations, inhibited cell proliferation, arrested cell cycle, and increased apoptosis	MTT assay/48 h	Bauer et al. (2016)
Processed mangokernel	—	LC_{50} 491.83 to 549.05 μg/mL	Brine shrimp lethality assay/24 h	Arogba (2014).
Onion extract with 60% alcohol	Human lymphocytes treated with bleomycin	Dose–response effect	Trypan blue exclusion assay/ 24 h	Cho et al. (2016).
Crude onion extract and fractioned extract (aqueous, methanolic, and ethyl acetate)	K562 and Lucena cells	For crude onion extract, cytotoxic effect at the concentration of 8 mg/mL after 24 h For aqueous and methanolic extract, cytotoxic effect at the concentration of 8 mg/mL after 72 h For ethylacetate extract, no significant cytotoxic effects Apoptosis increased at the concentration of 4 mg/mL	MTT assay/72 h	Votto et al. (2010)
Cranberry	SKOV-3, PC-3, LF	IC_{50} = 79–479 μg/mL	BrdU assay/42 h	Singh et al. (2009)
Gabiroba (*Campomanesia cambessedeana* Berg)	HepG2	EC_{50} 40.70 ± 4.86 mg/mL	MTS assay/72 h	Malta et al. (2013)
Murici (*Byrsonoma verbascifolia* Rich)	HepG2	EC_{50} 173.6 ± 18.2 mg/mL	MTS assay/72 h	Malta et al. (2013)

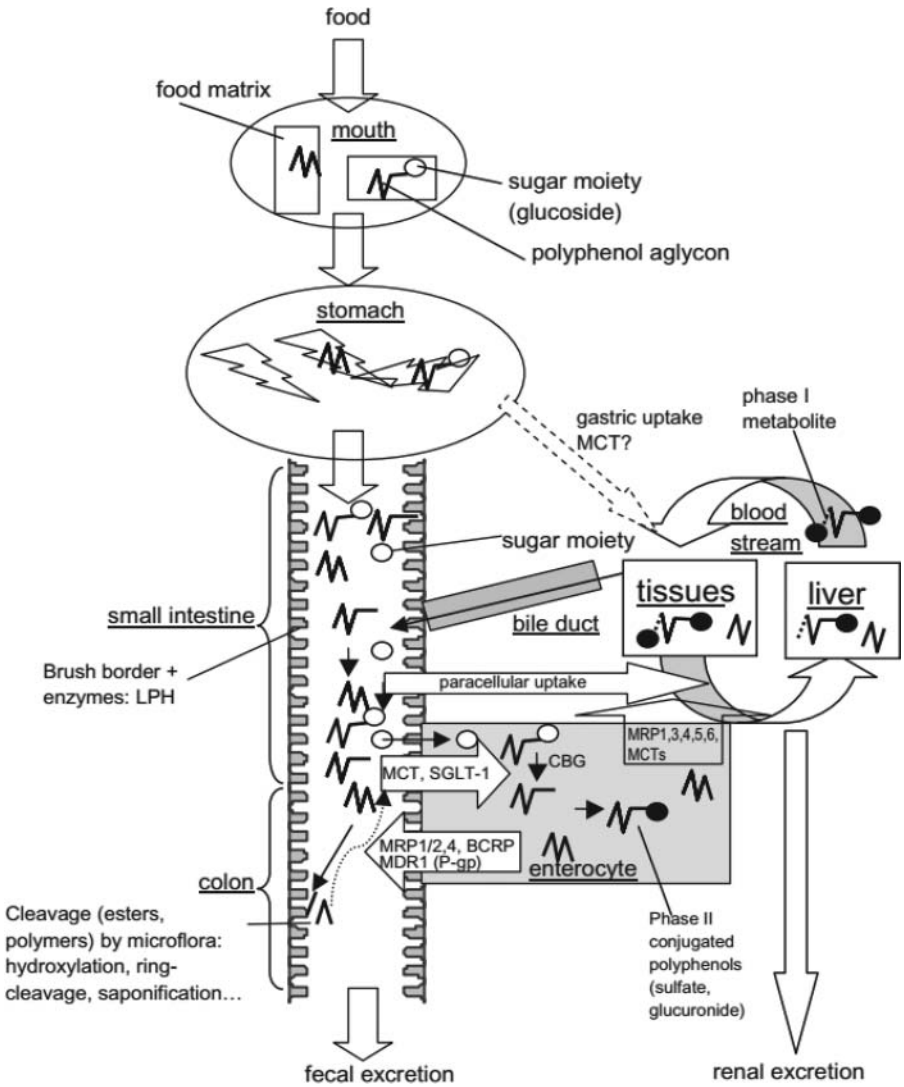

Figure 21. Overview of flavonoid absorption and transformation (adapted from Bohn, 2014). BRCP, breast cancer resistance protein; CBG, cytosolic β-glucosidase; LPH, lactase-phlorizin hydrolase; MCT, monocarboxylic acid transporter; MRP, multidrug resistance proteins; Pgp, P-glycoprotein; SGLT1, sodium-glucose linkedtransporter 1; MDR1, multidrug resistance protein.

ever, Gardana et al. (2007) observed that 95% of hesperetin from orange juice was in the conjugated form in human plasma. Quercetins are also present as different conjugated forms such as quercetin-3-*O*-glucuronide, 3′-*O*-methyl-quercetin-3-*O*-glucuronide, and quercetin-3′-*O*-sulfate in plasma (Manach et al., 2005). Another research from Graefe et al. (2001) mentioned that quercetin-4′-glucoside was absorbed in the small intestine through sodium-dependent glucose transporter and luminal hydrolysis by lactase-phlorizin hydrolase, whereas quercetin-3′-glucoside was absorbed in the colon through deglycosylation by lactase-phlorizin hydrolase. Soy isoflavone daidzein and resveratrol were converted to equol and dihydroresveratrol, respectively, in presence of microbial fermentation and showed more phytoestrogens as compared to initial compounds. However, the microflora fails to degrade tannins due to its complex structure (Bohn, 2014). Epigallocatechin-3-gallate is transported into the cell by passive diffusion and metabolized into methylated metabolites and glucuronides as well as metabolized was reduced by multidrug resistance proteins (Hong et al., 2002). Thus, there are many factors such as food matrix during gastric or small intestinal digestion, aglycone forms conjugated by enterocytes, microbial fermentation, phase I or II enzyme in the intestine or colon, blood stream transportation, and tissue distribution and excretion involved in the transfer of flavonoids (Bohn, 2014).

Conclusion

In recent years, food safety has been a major concern not only for the consumers but also for product developers. Moreover, consumers are more conscious about their health, leading to increased demand for nutritionally rich food with health benefits. Fruits and vegetables are good sources of flavonoids, but cannot be preserved in their fresh forms owing to their perishable nature. Therefore, various processing methods are needed to retain their nutritional values. However, processing has a strong impact on the nutritional value during storage of processed products. This review is focused on total and specific flavonoid contents of fruits and vegetables after thermal and nonthermal processing. This review provides additional information to consumers, researchers, and product developers about the effects of processing on flavonoids and focuses on the bioavailability and cytotoxicity of flavonoids as well as changes in the flavonoid pathway during thermal and nonthermal processing.

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