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Impact of thermal processing on dietary flavonoids

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Flavonoids are widely distributed in natural products and foods as a class of polyphenols. They processed diverse bioactivities, including anti-inflammation activity, antiaging activity, and antioxidant activity. The foods rich in flavonoids are usually consumed after thermal processing. However, flavonoids are commonly vulnerable under thermal processing, and it could cause various influences on their stability and bioactivities. Therefore, in this review, the effects of thermal processing on thermal stability and bioactivities of dietary flavonoids from different food sources were first summarized. The strategies to improve thermal stability of dietary flavonoids were then discussed. Noticeably, the effect of some of the promising thermal technologies on dietary flavonoids was also clarified preliminarily in the current review. The promising thermal technologies may be an alternative to conventional thermal processing technologies.

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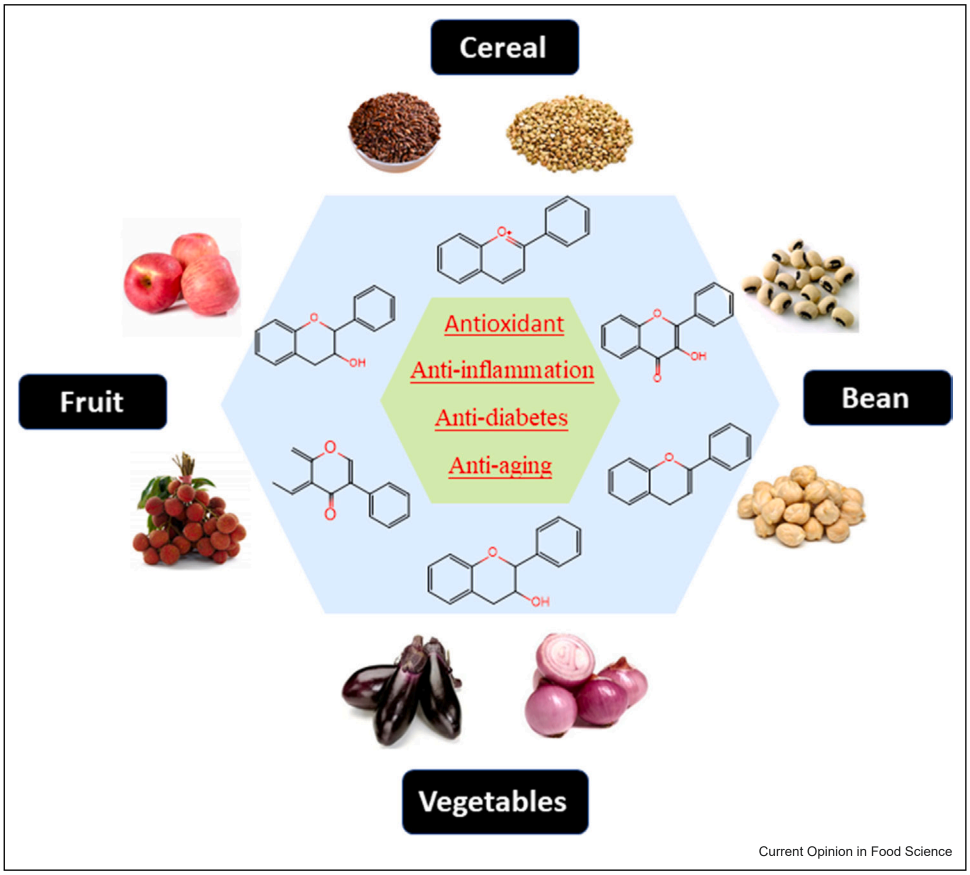
Introduction

Flavonoids are a class of polyphenols, with the typical chemical structures containing A, B, C three (C6–C3–C6) rings, including flavanols, flavones, isoflavones, flavanones, flavan-3-ols, and anthocyanidins [1–4]. Flavonoids mainly form fruits, vegetables, cereals and beans, have profitable advantages on human health, including anti-inflammation activity, antiaging activity, antioxidant activity, and antidiabetes activity (Figure 1) [5–10].

To meet the safety and shelf-life-stable requirements, the processing is inevitable for foods before delivering to consumers. Flavonoids are commonly vulnerable under different processing conditions, especially thermal processing. Thermal processing is a kind of widely used processing technique in the food industry and household cooking. The application of thermal processing has been favored by the important technological developments experienced over the last few years. During thermal processing, undesirable microorganisms and spoilage enzymes were inactivated, and gastrointestinal digestion of food generally enhanced [11,•12]. On the other hand, the quality of food (color, taste, nutrients, and bioactive compounds) is usually impaired by long-time heating, resulting in reduced bioavailability and organoleptic property destruction [13].

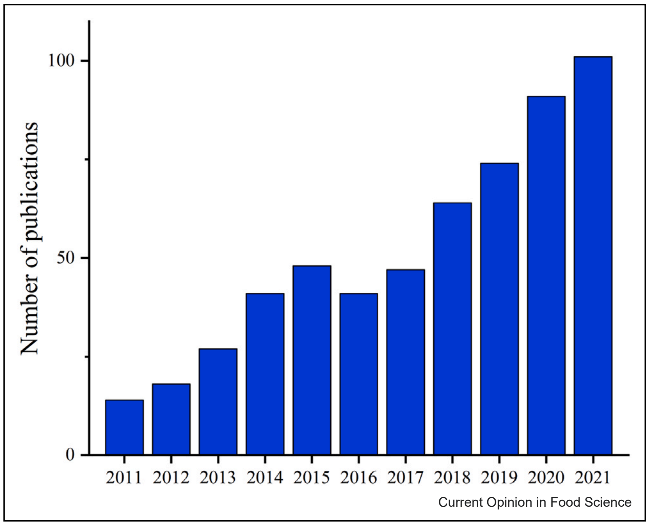
Usually, the dietary flavonoids are vulnerable under thermal processing, and their bioactivity usually impaired after thermal processing, due to their lower stability. Therefore, researches related to the impact of thermal processing on dietary flavonoids were explored to clarify the thermal satiability of flavonoids and bioactivity of dietary flavonoids after thermal processing, and establish strategies to improve thermal stability of dietary flavonoids. The factors, such as thermal processing techniques, heating temperature, heating time, and food matrices, influenced thermal stability of dietary flavonoids variously [•14–16]. Some strategies or new techniques were applied to improve thermal stability of dietary flavonoids, which is becoming a research hotspot [•17–19]. The number of publications (indexed by Pubmed) on “thermal processing and flavonoid” sharply increased since 2011 (Figure 2). Therefore, this review will mainly focus on the impacts of thermal processing on dietary flavonoids.

Figure 1



The main resources, chemistry structures, and bioactivities of dietary flavonoids.

Figure 2



The number of publications on "thermal processing and flavonoid" indexed by Pubmed database since 2011.

Influence factor of thermal processing on the thermal stability of dietary flavonoids

The intake of dietary flavonoids is conducive to reduce the risk of diseases, partly attributed to intake of dietary flavonoids therein. The roasting, barking, steaming, frying, and grilling are common thermal processing techniques in food industries (Table 1). However, the thermal stability of dietary flavonoids was easily influenced by different factors, such as thermal processing techniques, heating temperature, heating time, and food matrices. The impacts of thermal processing on flavonoid content in various food matrices under different conditions are shown in Table1.

The thermal stability of dietary flavonoids under different thermal conditions was distinct. For example, only frying (170 °C for 10 min) could increase total flavonoid content (TFC) of dark-purple eggplant (*Solanum melongena*), on the contrary, barking (180 °C for 30 min), boiling (100 °C for 20 min), and grilling (120 °C for 10 min) decreased its TFC [20] (Table 1). Contrary to eggplant, barking (180 °C for 30 min), frying (140 °C for

Table 1

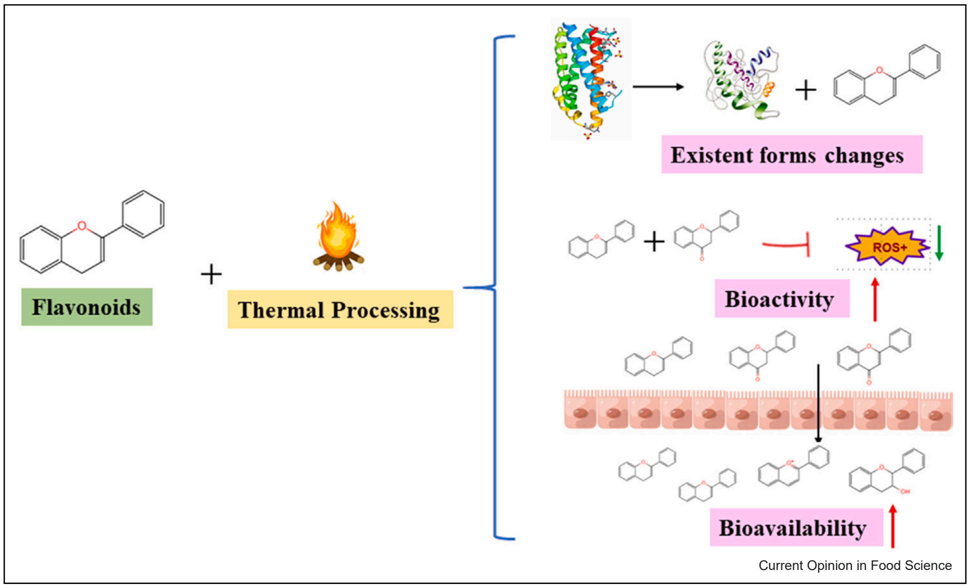
Impacts of thermal processing on flavonoid content in various foods.

Order	Food sources	Flavonoids	Processing method	Contents of flavonoids	Reference
1	Eggplant	TFC	Barking (180 °C for 30 min)	TFC[a]↓	Martini et al. [20]
			Boiling (100 °C for 20 min)	TFC↓	
			Frying (170 °C for 10 min)	TFC↑	
			Grilling (120 °C for 10 min)	TFC↓	
2	Onions	TFC	Barking (180 °C for 30 min)	TFC↑	Cattivelli et al. [16]
			Boiling (100 °C for 30 min)	TFC↓	
			Frying (140 °C for 8 min)	TFC↑	
			Grilling (110 °C for 15 min)	TFC↑	
3	Mulberry juice	TFC	Heating by water bath (25, 35, 45, 60, and 100 °C for 60 min)	TFC↓ in 15–45 °C treatment, TFC↑ in 45–100 °C treatment	Li et al. [•14]
4	Blueberry (*Vaccinium* spp.) puree	TAC	Heating (at 40, 50, 60, 70, 80, 90, and 100∘C for 20 min)	TAC[b] under 40–80 °C treatment, TAC↑ under 90 °C treatment, and TAC↓ under 100 °C treatment	Zhang et al. [8,21]
5	Teff (*Eragrostis tef*)	TFC	Roasting (180 °C ± 20 °C for 5–10 min)	TFC ↑ in roasting for 7.5 min, TFC ↓ in roasting for 10 min	Kataria, Sharma, & Dar [22]
6	Buckwheat bran	TFC, rutin, isoquercetin, and quercetin	Baking (180 °C for 30 min)	TFC, isoquercetin, and quercetin ↓rutin	Ge & Wang [23]
	Buckwheat flour	TFC, rutin, isoquercetin, and quercetin	Baking (180 °C for 30 min)	TFC, rutin, isoquercetin↑;quercetin↓	
7	Sesame (ganzhi9, ganzhi17, ji9014, ezhi7, and luozhi18)	TFC	Roasting (240 °C for 20 min)	TFC	Chen et al. [24]
	Sesame (Liaozhi8)			TFC↓	
8	Thai rice bran (Khao Dawk Mali 105)	Rutin, myricetin, quercetin-3-glucuronide, and TFC	Water-bath heat treatment (100 °C for 15 min)	Rutin, myricetin, TFC↓, and quercetin-3-glucuronide↑	Peanparkdee, Patrawart, & Iwamoto [25]
	Thai rice bran (Hom Nil)			Rutin↓ myricetin, TFC, and quercetin-3-glucuronide↑	
	Thai rice bran (Kiaw Ngu and Leum Pua)			Rutin, myricetin, TFC, and quercetin-3-glucuronide↓	
9	Canned lychee pulp	TFC	Heat treatment (70 °C and 121 °C for 30 min)	TFC↓	Wang et al.,[26]
10	Pomelo (citrus maxima) juice	TFC	Pasteurization	TFC↓	Basumatary et al. [27]
11	Common buckwheat and tartary buckwheat	Rutin, quercetin, and TFC	Steaming (120 °C for 20 min)	TFC of common buckwheat, TFC of tartary buckwheat↓, rutin↓, quercetin↑	Chen et al. [28]
			Roasting (150 °C for 20 min)	Rutin↑, quercetin↑, TFC	
12	Samh(*Mesembryanthemum forsskalei* Hochst) seeds	TFC	Roasting (150 °C for 10 min)	TFC↓	Ahmed et al. [29]
13	Jack bean (*Canavalia ensiformis* (L.) DC)	Anisoyl kaempferol glycosides	Heating (95 °C for 0, 2, 4, 8, 16, and 24 h)	Transferred to another two isomers	Sutedja et al. [30]

[a] TFC= total flavonoid content;

[b] TAC= total anthocyanin content; ↓ indicates content decreased, ↑ indicates content increased, - indicates content does not change.

Figure 3



Effects of thermal processing on the biological bioactivity of dietary flavonoids.

8 min), and grilling (110 °C for 15 min) improved TFC of onions, and boiling (100 °C for 30 min) reduced its TFC [16] (Table 1). It is hard to say that one certain thermal processing technique can improve or retain more dietary flavonoids. Obviously, the thermal processing method is a significant interfering factor influencing satiability of dietary flavonoids.

The temperature of thermal processing is one of the critical factors to affect thermal satiability of dietary flavonoids. For example, 25–45 °C thermal treatment, the TFC of mulberry juice was decreased, however, 45–100 °C thermal treatment increased its TFC [•14] (Table 1). The total anthocyanin concentrations of blueberry (*Vaccinium* spp.) puree were changed strangely under different temperature treatment (Table1) [21]. Processing time is another major factor affecting dietary flavonoid satiability. The TFC of teff (*Eragrostis tef*) was increased within 7.5 min of roasting, and decreased after 10 min, which indicated that thermal processing time may be one of the major factors affecting TFC in roasting [22] (Table 1).

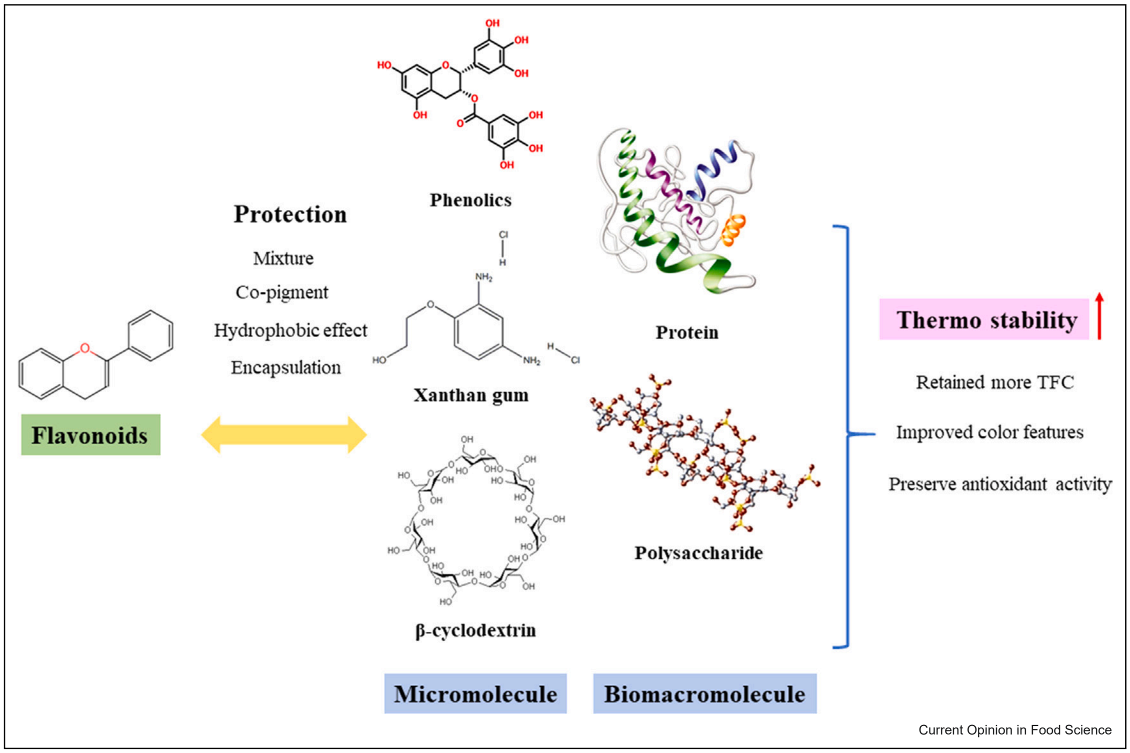
Even at the same heating temperature and time, the thermal stability of dietary flavonoids was a noticeable difference in different food matrices. For example, barking at 180 °C for 30 min leads to decreasing of isoquercetin, quercetin, TFC in buckwheat bran, and increasing of isoquercetin, rutin, and TFC in buckwheat flour [23] (Table 1). The thermal satiability of different varieties was various, as evidenced by a marked reduction in TFC in Liaozhi8 sesame after roasting, however, no significant influence on TFC change in ganzhi9, ganzhi17, ji9014, ezhi7, and luozhi18 sesame [24] (Table 1). The thermal stability of foods in different states is also diverse. It was also found that steaming could retain more anthocyanins than boiling for solid-state food, and boiling was preferable for liquid food [15].

For further quantitatively describing the impact of temperature on degradation, the kinetics of degradation of dietary flavonoids were investigated. The thermal degradation of anthocyanins followed a first-order kinetic model, and the kinetic rate constant increased with temperature raised [15,••31]. However, the thermal degradation of TFC in button mushroom (*Agaricus bisporus*) was followed by second-order kinetic model, with the activation energy 25.38 kJ/mol [32]. In the thermal processing, the dietary flavonoids seemly were rearrangement, hydrolysis, and cleavage of glycosidic bonds, which lead to degradation of the matrix, resulting in an apparent increase [30,33].

Effect of thermal processing on biological bioactivity of dietary flavonoids

Flavonoids have many biological activities, such as antioxidant, anti-inflammation, and prevention of cardiovascular disease activities. Dietary flavonoids are sensitive to thermal condition, however, some research found that thermal processing can promote its biological bioactivity (Figure 3). The thermal processing techniques decreased flavonoid contents of eggplants, however, promoted their bioavailability on the contrary [20].

Figure 4



Strategies to improve thermal stability of dietary flavonoids.

Antioxidant activities of six flavonoids (rutin, naringin, eriodictyol, mesquitol, luteolin, and 7-*O*-glucoside) improved after thermal processing (from 30 to 130 °C), and their thermal-product solutions increased activities of intracellular superoxide dismutase and glutathione peroxide [34].

Even through thermal processing exerted negative effect inducing flavonoid degradation, some reactions occurred. The heat destroys cell walls and makes bound flavonoids hydrolyzed [30,35], which promoted the configuration of flavonoids from transformation of soluble flavonoids to insoluble-bound flavonoids, and flavonoid glycosides to aglycones [36,•37]. The biological bioactivity of dietary flavonoids is closely related to their configuration, which may improve their biological bioactivity after thermal processing.

Strategies to improve thermal stability of dietary flavonoids

The use of flavonoid-rich products in food industries and house-cooking is limited by their thermal stability. Considering the low thermal stability of flavonoids, therefore, the strategies to improve thermal stability of dietary flavonoids are encouraged [•17,19]. The studies related to the effects of bioactive ingredient addition to improve the thermal stability of dietary flavonoids were performed (Figure 4). The buckwheat in different concentrations partially replaced rice noodles, which exhibited a high TFC-retention rate of rice noodles after thermal processing [38]. In addition, the xanthan gum or phenolics supplementation also preserved thermal stability of dietary flavonoids after heat treatment [39,40]. The β-cyclodextrin microcapsule technology is a promising strategy to improve the thermal stability of mulberry flavonoids, by retaining 90% TFC after 100 °C heating treatment [•14]. Recently, the use of biomacromolecule to improve the thermal stability of flavonoids has been widely studied, such as protein and polysaccharide (Figure 4). The pectic polysaccharide interacted with malvidin-3-*O*-β-D-glucoside to improve its thermal stability [•41]. The silkworm pupa protein–glucose conjugates combined with cyaniding 3-*O*-glucose via hydrophobic interactions and static quenching, and therefore enhancing its thermal stability over a pH range [42].

The effects of promising thermal technologies on dietary flavonoids

The conventional thermal processing (e.g. barking, roasting, pasteurization, and steaming) is frequently queried, due to their low processing efficiency and penalty of nutrients in food. The novel thermal techniques, such as microwave, radiofrequency, and ohmic heating with short time and low temperature, are regarded as promising thermal processes and possess great potential to replace conventional thermal processing. Microwave heating is usually utilized combined with conventional thermal processing techniques. The utilization of microwave heating can effectively shorten processing time and costs, and therefore can preserve more flavonoid contents than conventional thermal processing [43]. For example, with the aid of microwave (450 W) combined with hot-air drying of cherry tomato, the retention of TFC and lycopene was superior compared with conventional air-drying alone at 65 ∘C [44]. Radio-frequency heating is a kind of dielectric heating-based technique, which can easily penetrate into the inside of the food matrix, and seems to retain more of dietary flavonoids than conventional techniques [45]. Hot-air-assisted radio-frequency heating (100–105 °C, 15 min, and 110–115 °C, 6 min) that stabilized rice bran demonstrated higher free flavonoid content than extruded rice bran, which provides useful information for stabilization method for rice bran [46]. Ohmic heating is an electroconductive heating treatment, which is able to influence the internal of food matrix, and conducive to better retention of dietary flavonoids [47]. The ohmic heating is capable of disrupting food matrixes and modulating internal components, which could increase free flavonoid content in grape than other conventional techniques [48]. In general, the innovative thermal processing techniques probably retained more flavonoids in some situation, depending on its intensity and aims [••18]. The lower temperature and shorter time of food processing are conducive to the retention of flavonoids. Additionally, the equipment of some promising thermal technologies is not suitable for household cooking, and their application in household cooking needs to be further explored.

Conclusion and perspective

The thermal processing is usually used to inactivate pathogens and undesirable enzymes, which is the most widespread processing method for food industry and household cooking. However, the dietary flavonoids are vulnerable, and easily degraded or converted into various derivatives under thermal processing. On the other hand, some kinds of flavonoids can be released from the food matrix during processing. The flavonoid contents and their bioactivities changed variously under different food matrices and thermal processing conditions. The variations of bioactivities were not in conformity with their contents and stabilities. However, the change mechanism of dietary flavonoids and their thermal- degradation products in food matrices during thermal processing were not studied thoroughly. This is probably because the reaction between dietary flavonoids and other components in food matrices is complicated and their change patterns are hard to clarify. In order to maintain the stability of dietary flavonoids, the innovative thermal processing techniques with shorter time and lower temperature treatment were emerged, such as microwave, radiofrequency, and ohmic heating. Some equipment of promising thermal technologies may not be suitable for household cooking, which limited their application in household cooking. Overall, these innovative techniques need to be further studied in the food industry and household cooking to improve the thermal satiability of dietary flavonoids.

Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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