DOI 10.1002/mnfr.201400494 *Mol. Nutr. Food Res.* 2015, *59*, 160–170

RESEARCH ARTICLE

Effects of food processing on polyphenol contents: A systematic analysis using Phenol-Explorer data

Joseph A. Rothwell[1], Alexander Medina-Remón[2,3], Jara Pérez-Jiménez[4], Vanessa Neveu[1], Viktoria Knaze[1], Nadia Slimani[1] and Augustin Scalbert[1]

[1] International Agency for Research on Cancer (IARC), Nutrition and Metabolism Section, Biomarkers Group, Lyon, France
[2] Department of Internal Medicine, Hospital Clínic, Institut d'Investigacions Biomédiques August Pi i Sunyer (IDIBAPS), University of Barcelona, Barcelona, Spain
[3] CIBER CB06/03 Fisiopatología de la Obesidad y la Nutrición (CIBERObn), Girona, Spain
[4] Institute of Advanced Chemistry of Catalonia (IQAC-CSIC), Barcelona, Spain

Received: July 21, 2014
Revised: October 10, 2014
Accepted: October 15, 2014

Scope: The Phenol-Explorer web database (http://www.phenol-explorer.eu) was recently updated with new data on polyphenol retention due to food processing. Here, we analyze these data to investigate the effect of different variables on polyphenol content and make recommendations aimed at refining estimation of intake in epidemiological studies.

Methods and results: Data on the effects of processing upon 161 polyphenols compiled for the Phenol-Explorer database were analyzed to investigate the effects of polyphenol structure, food, and process upon polyphenol loss. These were expressed as retention factors (RFs), fold changes in polyphenol content due to processing. Domestic cooking of common plant foods caused considerable losses (median RF = 0.45–0.70), although variability was high. Food storage caused fewer losses, regardless of food or polyphenol (median RF = 0.88, 0.95, 0.92 for ambient, refrigerated, and frozen storage, respectively). The food under study was often a more important determinant of retention than the process applied.

Conclusion: Phenol-Explorer data enable polyphenol losses due to processing from many different foods to be rapidly compared. Where experimentally determined polyphenol contents of a processed food are not available, only published RFs matching at least the food and polyphenol of interest should be used when building food composition tables for epidemiological studies.

Keywords:
Food composition / Food processing / Phenol-Explorer database / Polyphenols / Retention factors

Additional supporting information may be found in the online version of this article at the publisher's web-site

1 Introduction

Polyphenols are a large and complex family of phytochemicals whose consumption from plant foods may offer protection against cardiovascular diseases, type II diabetes, cancers, and other health benefits [1]. Polyphenols are subdivided into numerous classes and subclasses and range from simple phenolic acids to high molecular weight compounds with up to 15 phenolic groups. The classes of greatest dietary importance are flavonoids, characterized by their three-ring skeleton, and phenolic acids, usually consumed as hydroxycinnamic and hydroxybenzoic derivatives. Phenol-Explorer (http://www.phenol-explorer.eu), a web database on polyphenols, contains detailed polyphenol compositions of over 450 foods [2]. These data are particularly valuable for the study of associations between polyphenol intake and health and, e.g. have been used to calculate the polyphenol intakes of cohort study subjects from dietary questionnaires [3, 4].

Phenol-Explorer has recently been enhanced with data on the effects of food processing on the polyphenol contents of foods [5]. Food processing often causes losses in polyphenol

Correspondence: Dr. Augustin Scalbert, International Agency for Research on Cancer (IARC), Nutrition and Metabolism Section, Biomarkers Group, 150 Cours Albert Thomas, F-69372 Lyon Cedex 08, France
E-mail: scalberta@iarc.fr

Abbreviations: **CA**, caffeic acid; **CQA**, caffeoylquinic acid; **Q3Rut**, quercetin 3-*O*-rutinoside; **IQR**, interquartile range; **RF**, retention factor

content, usually brought about by oxidation, enzymatic action, removal of skin or seeds, and leaching into oil or water that is then discarded [6]. Simpler derivatives may increase in concentration upon the breakdown of others. For some widely consumed processed foods such as coffee, orange juice, and wine, experimentally determined polyphenol contents are already available. For other foods often consumed after processing, contents must be estimated based on that of the raw plant food postharvest. In these cases, the effect of processing can be accounted for by multiplying raw food polyphenol content by a retention factor (RF), a predetermined fold change in polyphenol content due to processing. RF < 1 indicates a reduced polyphenol content in the processed food whereas RF $= 1$ and RF > 1 indicate full retention or an increase, respectively [7].

To construct the food processing update, as many RFs as possible were calculated from published data, each specific to a combination of food, process, and polyphenol. This is necessary because even small variations in structure cause large changes in chemical activity, and each food matrix represents a unique physicochemical medium [8]. Phenol-Explorer RFs were standardized by adjusting for loss of weight during processing and similar data aggregated and averaged. All data, and their sources, can be retrieved through the food processing section of the Phenol-Explorer web interface. These new data have many applications but, in particular, will allow epidemiologists to improve estimation of individual intake in cohort studies where previously only content data from raw foods was used [9] or RFs were used but based on one food only [3]. Cooking methods are often indicated in or can be deduced from dietary questionnaires, and these data should be considered when estimating intake.

A detailed subclass-by-subclass account of polyphenol losses due to processing has already been published [10]. The aim here was to analyze the standardized Phenol-Explorer food processing dataset to describe the effects of processing in more quantitative terms, facilitating the comparison of different processes and allowing decisions to be more easily taken on the adjustment of polyphenol content of processed foods. In particular, we wish to clarify the influence of different variables upon polyphenol losses due to processing, and search for rules that could be used to adjust for processing losses where only the content of the raw food is known and no corresponding RF is available. Greater importance is given to the most commonly consumed polyphenols, foods, and domestic cooking methods.

2 Materials and methods

2.1 Update of Phenol-Explorer with food processing data

Data on polyphenol loses due to food processing were collected from peer-reviewed publications on food processing, nutrition, and polyphenol chemistry as described by Rothwell et al. [5]. RFs were calculated according to Eqs. (1) and (2) as follows:

$$\text{Retention factor } (RF) = \frac{\text{concentration of polyphenol in processed food}}{\text{concentration of polyphenol in raw food}} \times \text{yield factor} \quad (1)$$

$$\text{Yield factor} = \frac{\text{weight of food after processing}}{\text{weight of food before processing}} \quad (2)$$

If necessary, one of 164 published yield factors was assigned to food–process combinations to account for change in weight due to processing and enable the changes in polyphenol content of different foods and processes to be compared. These were collected mainly from EUROFIR food yield and nutrient retention tables (http://www.langual.org) and the USDA National Nutrient Database for Standard Reference (http://www.ars.usda.gov/ba/bhnrc/ndl). Where no exact match existed for both food and process, the closest possible yield factor was used. Individual RFs were calculated before being aggregated and averaged to obtain a single value for each combination of polyphenol, food, process, and analytical method. All polyphenol contents before and after processing, yield factors, and published data sources are retrievable from the Phenol-Explorer website.

2.2 Treatment of different analytical methods

Publications collated for the database used different methods of analysis to determine polyphenol loss due to processing. To compare data, it is important to distinguish between the quantitation of well-defined polyphenols native to foods, such as quercetin 4′-*O*-glucoside, and grouped compounds such as quercetin derivatives or total anthocyanins. Those publications that measured well-defined compounds used HPLC with no prior hydrolysis of polyphenol glycosides or esters. Compounds studied using this method were usually conjugates, since aglycones are not normally native to foods. Other publications used a hydrolysis step prior to analysis to release polyphenol aglycones from sugar and ester moieties, effectively grouping all derivatives of one aglycone before determining changes due to processing. A number of studies also used the Folin–Ciocalteu assay to measure total phenolics before and after processing, and a few used the pH differential method to measure total anthocyanins. Data were therefore interpreted according to the analytical method used and whether a group of polyphenols or a single well-defined polyphenol was under study.

2.3 Statistical analysis

RFs for well-defined and grouped compounds were pooled separately and median and interquartile ranges (IQRs)

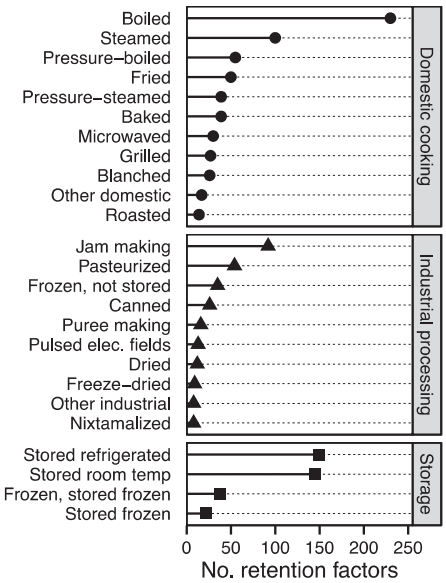

Figure 1. Frequency of aggregated retention factors in Phenol-Explorer by process and process type.

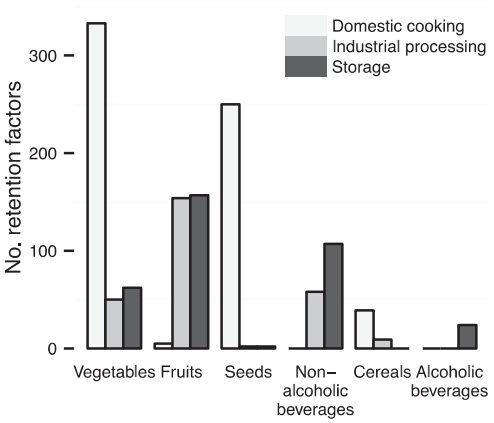

Figure 2. Profile of retention factors by food group and process type.

calculated for the most commonly studied process, foods, and polyphenols. Specific examples for which enough data were available were then chosen for more detailed analysis. These consisted of the polyphenols caffeic acid (CA), 5-caffeoylquinic acid (5-CQA), quercetin and quercetin 3-*O*-rutinoside (Q3Rut), the foods black bean and potato, and the domestic process boiling. Statistical analyses and data visualizations were performed using Microsoft Excel and R open-source statistical software.

3 Results

3.1 Food processing data collated in Phenol-Explorer

The 143 original publications used produced 4296 individual RFs. Automatic aggregation of these individual values by food, polyphenol, process, and analytical method generated a new set of 1253 RFs, of which around half were averages of multiple values (Supporting Information Fig. 1). The term *RF* will henceforth refer to the values from this new dataset only unless otherwise stated.

Vegetables, fruits, and seeds were most frequently studied, particularly potato, tofu, tomato, and bean. Boiling was the most studied process ($n = 230$), although fresh and frozen storage together accounted for a quarter of all data ($n = 316$; Fig. 1). Domestic cooking was most often studied for vegetables and seeds, whereas storage and industrial processing were more studied for fruits and beverages (Fig. 2). A total of 161 polyphenols or groups of polyphenols were covered. Most were individual polyphenols identified and quantitated by HPLC, but a number of RFs correspond to groups of compounds, most notably total phenolics as determined by the Folin assay, but also total anthocyanins and some proanthocyanidin oligomers (e.g. 02–03 mers and 07–10 mers). Around half of the 1253 RFs described changes in individual flavonoid content, mostly from the anthocyanin and flavonol subclasses (Supporting Information Fig. 2). A further 392 RFs described changes in phenolic acid and 224 changes in total phenolics content. The most studied individual polyphenols were 5-CQA, quercetin, CA, and Q3Rut.

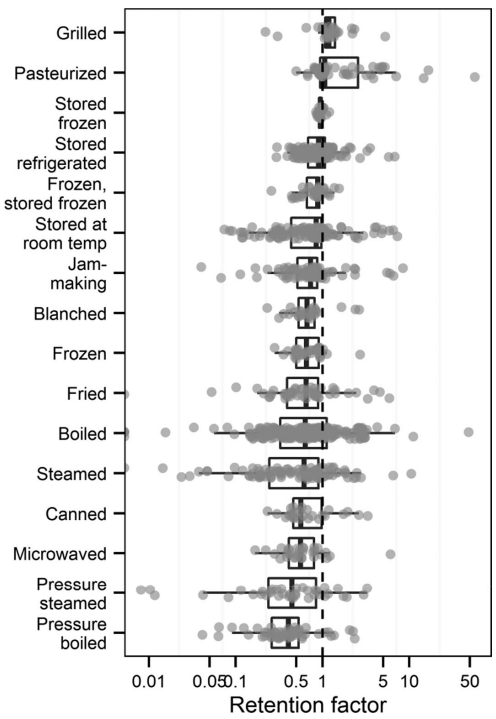

Figure 3. Spread of retention factors for the 16 most frequently studied processes (all compounds and compound groups). RFs are plotted on a log scale and polyphenol content prior to processing is indicated by the dotted line (RF = 1).

Table 1. Overall changes in polyphenol content according to types of food processing in Phenol-Explorer

Process	No. of raw data (raw RFs)	No. of aggregated RFs	Principal foods of interest	Principal polyphenols of interest	Retention factor (aggregated, excluding total polyphenols)			
					Well-defined polyphenols[a)]		Grouped polyphenols[b)]	
					Median	IQR	Median	IQR
Stored at room temperature	1316	145	Orange juice, red wine, tomato juice and ketchup, strawberry jam	Caffeic acid, ferulic acid, cyanidin 3-*O*-glucoside, quercetin	0.81	0.64	0.88	0.16
Stored refrigerated	910	149	Sweet cherry, strawberry juice, spinach, blueberry	Cyanidin 3-*O*-glucoside, pelargonidin 3-*O*-glucoside, ellagic acid	0.84	0.44	0.95	0.25
Boiled	496	230	Soy, potato, beans, chestnut, broccoli	5-Caffeoylquinic acid, quercetin 3-*O*-rutinoside, caffeic acid, quercetin	0.66	1.02	0.59	0.71
Frozen, stored frozen	167	37	Blackcurrant, cauliflower, carrot, pea	Quercetin, ellagic acid	0.87	0.31	0.88	0.21
Jam making	142	92	Blueberry, strawberry	Quercetin, kaempferol	0.68	0.51	0.73	0.22
Pasteurized	142	54	Tomato, grape juice, pomegranate, strawberry	Quercetin, cyanidin 3-*O*-glucoside	1.15	1.74	1.00	0.1
Steamed	114	100	Beans, carrot, cauliflower	5-Caffeoylquinic acid, caffeic acid, sinapic acid	0.34	0.71	0.67	0.62
Stored frozen	111	22	Raspberry, blackberry	Ellagic acid, cyanidin 3-*O*-glucoside, cyanidin 3-*O*-sophoroside	1.02	0.04	0.92	0.05
Fried	92	50	Tofu, artichoke	Ferulic acid, quercetin	0.83	1.41	0.50	0.38
Microwaved	83	30	Potato, spinach	4- and 5-Caffeoylquinic acid, protocatechuic acid	0.56	0.39	0.56	0.39
Baked	82	39	Potato, wheat flour	Ferulic acid, 4- and 5-caffeoylquinic acid	0.76	0.59	1.09	0.78
Pressure-boiled	80	55	Bean, pea, artichoke	Caffeic acid, 5-caffeoylquinic acid	0.31	0.24	0.46	0.22
Roasted	60	14	Peanut, chestnut	*p*-Coumaric acid, gallic acid	2.59	0.52	0.84	0.63
Canned	58	38	Tomato	Quercetin, naringenin	0.60	0.63	0.46	0.22
Blanched	56	26	Cauliflower, cabbage	Quercetin, kaempferol	2.03	1.01	0.58	0.25

a) Well-defined polyphenols from food extracts not hydrolyzed prior to processing.
b) Changes in polyphenol content measured after hydrolysis of food extracts, e.g. all derivatives of particular aglycones, grouped subclasses, or total phenolics.
RF, retention factor.

Most RFs were less than 1, indicating loss of polyphenol, although a considerable number fell above this threshold, particularly in the range RF = 2–5 (Supporting Information Fig. 3). These data usually corresponded to increases in the contents of well-defined polyphenols from food extracts that were not hydrolyzed prior to analysis and could therefore be produced from the breakdown of more complex derivatives.

Although data on well-defined polyphenols are most useful for characterizing specific trends, data on grouped polyphenols (hydrolyzed and total phenolics) may also give an overview of polyphenol loss without interference from phenolic by-products of hydrolysis. RFs were much less variable for grouped compounds, determined after hydrolysis of food extracts, than for well-defined compounds, whose losses may be masked by the breakdown of more complex polyphenol derivatives. Here, the overall effect of processes, foods, and polyphenol structure on loss is compared using grouped compounds only, while specific examples usually refer to data on well-defined polyphenols.

3.2 Influence of process upon polyphenol loss

Most of the frequently studied processes produced a wide range of RFs, suggesting a strong influence of other variables (Fig. 3). Domestic processes tended to cause loss of polyphenol. For grouped compounds, the median RF due to boiling was 0.59 with an IQR of 0.71. A similar distribution was observed for steaming (median RF = 0.67, IQR = 0.62), while frying produced slightly less variable results (median RF = 0.5, IQR = 0.38). In contrast, storage at room temperature (median RF = 0.88, IQR = 0.16), refrigeration (median RF = 0.95, IQR = 0.25), and frozen storage (RF = 0.92, IQR = 0.05) caused milder overall losses. Polyphenol losses due to jam-making were also mild (RF = 0.73, IQR = 0.22), although a narrower range of foods and polyphenols is covered. Data are summarized in Table 1.

Extensive data were collected on changes in the contents of the flavonols quercetin and Q3Rut due to different processing methods [11–25]. Both boiling and frying caused considerable losses of quercetin derivatives from broccoli (RF = 0.22 and 0.21, respectively), but fewer were lost upon steaming (0.64; Fig. 4A). Steaming also caused milder losses of quercetin derivatives from carrot than did boiling (RF = 0.89 and 0.37, respectively). However, losses of quercetin derivatives from onion were similar whether blanched, boiled, fried, or microwaved (0.42–0.54). Free quercetin content increased upon the blanching and steaming of common cabbage and cauliflower, although this would usually represent only a minor portion of all quercetin derivatives. Losses of Q3Rut from peeled potato varied little with different cooking methods (RF = 0.39–0.54; Fig. 4B), and Q3Rut in carrot was affected similarly by boiling and steaming. In contrast, cauliflower lost almost all Q3Rut through boiling but retained most through steaming (0.08 and 0.76, respectively).

3.3 Relative sensitivity of different foods to polyphenol loss

Overall losses of polyphenols from potato were relatively mild regardless of process (median RF = 0.7, IQR = 0.04; Table 2). Polyphenol losses were particularly severe from black beans (median RF = 0.31, IQR = 0.22), other beans

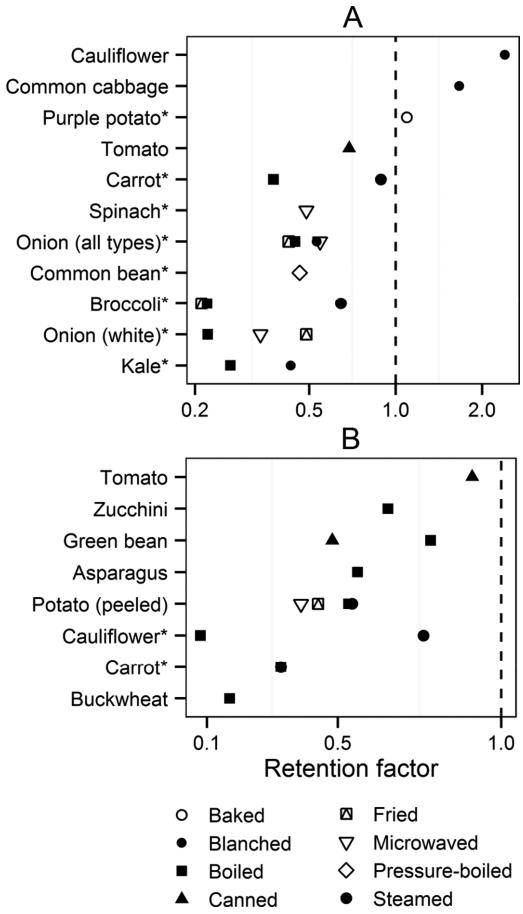

Figure 4. Change in contents of (A) quercetin and (B) quercetin 3-rutinoside in various plant foods due to different domestic cooking processes. Foods marked by asterisks were analyzed after a hydrolysis step and polyphenols measured may therefore represent heavier molecular weight derivatives. RFs are plotted on a log scale and polyphenol content prior to processing is indicated by the dotted line (RF = 1).

(median RF = 0.31, IQR = 0.2), and pigeon pea (median RF = 0.48, IQR = 0.18). Data on strawberry and blueberry were also numerous and losses were generally mild, although processes were restricted to jam and puree-making. Losses of polyphenol from tomato and carrot were more variable due to the wide range of polyphenols found in each food. It is necessary to examine individual polyphenols and processes in these cases.

CA and its quinic acid ester, 5-CQA, are found in many plant foods and serve to illustrate variation in sensitivity to polyphenol loss [14, 15, 19, 20, 26–32]. 5-CQA losses often varied more with food than with process and, for some foods, losses due to different cooking methods were similar (Fig. 5A). Zucchini, bean, carrot, and broccoli were most sensitive to 5-CQA loss. CA was, in most cases, measured after hydrolysis of food extracts, and therefore may represent total CQAs. Differences in compound retention between foods were similar to those seen for 5-CQA (Fig. 5B). The free CA

Table 2. Overall changes in polyphenol content in the most commonly processed foods in Phenol-Explorer, excluding data from storage processes

Food occurrence	No. of original RFs	No. of aggregated RFs	Principal processes of interest	Principal polyphenols or polyphenol classes of interest	Retention factor (aggregated, excluding total polyphenols)			
					Well-defined polyphenols[a)]		Grouped polyphenols[b)]	
					Median	IQR	Median	IQR
Potato, peeled	116	29	Boiled, microwaved, baked	3-, 4-, and 5-Caffeoylquinic acid, caffeic acid	0.54	0.41	0.7	0.04
Tofu	101	23	Boiled, fried	Daidzein, genistein	2.76	2.16	-	-
Tomato	100	33	Canned, pasteurized	Quercetin, naringenin	2.62	3.71	0.83	0.53
Black bean	93	92	Boiled, steamed	Sinapic acid, gallic acid	0.34	0.46	0.31	0.22
Bean (other)	78	76	Boiled, steamed	Sinapic acid, gallic acid, protocatechuic acid	0.29	0.20	0.31	0.20
Strawberry	57	16	Jam and puree making	Pelargonidin 3-glucoside, pelargonidin 3-rutinoside, cyanidin 3-glucoside	0.66	0.20	0.77	0.26
Pigeon pea	52	7			-	-	0.48	0.18
Potato	47	11	Boiled	Caffeic acid, 5-caffeoylquinic acid	0.62	0.08	0.95	0.42
Carrot	45	28	Boiled, steamed	5-Caffeoylquinic acid	0.53	0	0.75	0.78
Chestnut	44	4	Roasted boiled	Gallic acid	1.76	0.31	1.20	0.38
Broccoli	43	29	Boiled	Quercetin, kaempferol	0.23	0.10	0.49	0.46
Blueberry	42	24	Jam making	Proanthocyanidin polymers, anthocyanins	0.68	0.15	0.75	0.09
Fig	42	7	Dried	Flavonols, flavanols, 5-caffeoylquinic acid	2.38	0.77	-	-
Barley, hulled	40	2	Extruded	Total polyphenols	-	-	0.57	0.01
Dried pea	40	8	Soaked	Total polyphenols	-	-	0.48	0.34

a) Well-defined polyphenols from food extracts not hydrolyzed prior to processing.
b) Changes in polyphenol content measured after hydrolysis of food extracts, e.g. all derivatives of particular aglycones, grouped subclasses, or total phenolics.
RF, retention factor.

content of peeled potato, globe artichoke, and eggplant increased upon cooking, presumably due to a simultaneous hydrolysis of different CQA esters. These data suggest that these hydroxycinnamates are sensitive to all domestic cooking methods and that their food source influences this sensitivity more than the process to which it is subjected.

3.4 Relative sensitivity of different polyphenols according to their structures

Storage processes excluded, the median RF for total phenolics was 0.74 ($n = 163$), corresponding to an overall loss of polyphenols. In terms of individual polyphenols, most data were available on the flavonols quercetin, kaempferol, and Q3Rut and the hydroxycinnamates 5-CQA, caffeic, ferulic, sinapic, *p*-coumaric, gallic and protocatechuic acids (Table 3). RFs for well-defined compounds (those measured without hydrolysis of extracts) were highly variable (IQR > 1). RFs for grouped compounds were less variable and median RFs were usually 0.5 or lower. Contents of 5-CQA, e.g. were reduced substantially overall by processing (median RF = 0.38, IQR = 0.4). Losses of protocatechuic and vanillic acids, for which variability was also low, were also extensive (median RF = 0.38 and 0.49 with IQR = 0.27 and 0.29, respectively).

Polyphenol losses from common black bean are particularly well characterized [27, 33]. Changes in contents of 22

polyphenols from a range of subclasses were calculated after boiling, steaming, pressure-boiling, and pressure steaming of this food (Fig. 6). The most poorly retained compounds were malvidin, petunidin, and delphinidin glycosides, which were almost totally lost upon any cooking method. Although retention varied widely between polyphenols, many were affected similarly by the four processes studied. Contents of some small phenolic acids, such as *p*-coumaric, ferulic, sinapic, gallic, and protocatechuic acids, increased upon processing, presumably due to their production via the breakdown of more complex polyphenols.

Polyphenol losses from potato are also well documented. Three quercetin glycosides were each lost extensively from potato regardless of cooking method, although losses of 3-, 4-, and 5-CQA were generally less severe [18, 34]. Losses of these three CQA esters due to microwaving and steaming were accompanied by increases in CA content, again suggesting hydrolysis during cooking.

Boiling was the domestic process on which most data were collected for Phenol-Explorer [11–18, 26, 34–40]. Broccoli was particularly sensitive to boiling, with extensive losses of most polyphenols, particularly kaempferol and quercetin monoglycosides (RF < 0.3; Supporting Information Fig. 4). In boiled cauliflower, Q3Rut was most extensively lost, but other polyphenols were better retained. Losses of flavonol glycosides from boiled potato, onion, and green bean were relatively mild, with the latter retaining most of its quercetin 3-rhamnoside and Q3Rut (RF $= 0.8$ for both). The contents of some polyphenols increased or were largely retained due to boiling, particularly those of hydroxycinnamic acids. CA content increased in broccoli, as did that of *p*-coumaric acid in carrot. No net losses of 3- and 5-CQA were observed in peeled potato and cauliflower, respectively. CA content also increased upon the boiling of black beans (RF $= 1.16$), corresponding to a decrease in 5CQA (RF $= 0.45$).

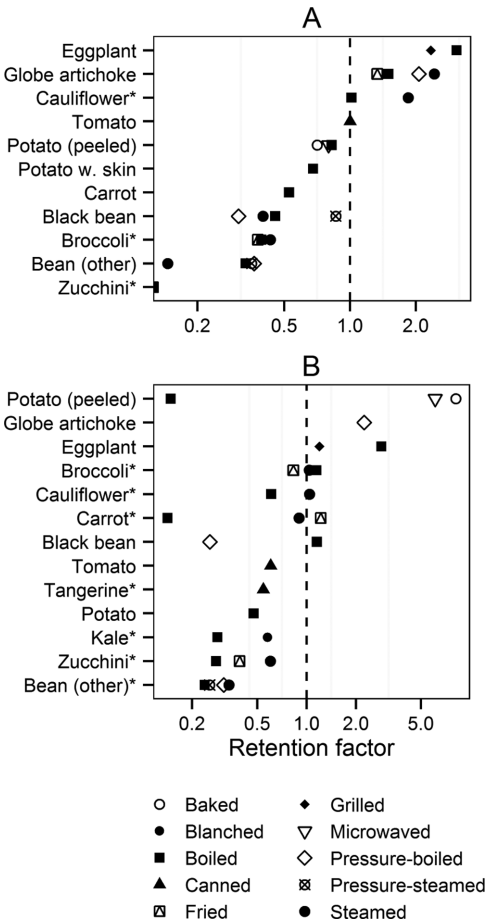

Figure 5. Change in contents of (A) 5-caffeoylquinic acid and (B) caffeic acid in various plant foods due to different domestic cooking processes. Foods marked by asterisks were analyzed after a hydrolysis step and polyphenols measured may therefore represent heavier molecular weight derivatives. RFs are plotted on a log scale and polyphenol content prior to processing is indicated by the dotted line (RF $= 1$).

4 Discussion

RFs were collected for Phenol-Explorer for a wide range of processes, foods, and polyphenols. Generally, availability of data for given processes, foods, or polyphenols reflected importance to human diets. For example, the large volume of data on 5-CQA and CA corresponds to the high intake of these phenolic acids, at least in Western diets [41]. In some cases, however, this was not true; e.g. data on polyphenol retention due to domestic cooking was abundant, but those on industrial processing such as canning and drying were much more limited, particularly given the importance to all diets of these common operations. In addition, industrial processing is made more complex by the combination of unit operations, such as where freezing of vegetables is preceded by blanching to denature enzymes [6], and published data were most often from laboratory simulations of industrial processes. Further research is needed on polyphenol losses from industrially processed plant foods. Likewise, few data are available on polyphenols in cereals and oils, and in terms of specific polyphenol subclasses, no data were available on procyanidin polymers at the time of compilation.

RFs collected for Phenol-Explorer data were obtained from many publications and, uniquely, data have been standardized to take into account weight change, which previously hindered comparison of polyphenol loss between different foods [6]. The majority of the data corresponded to polyphenol loss due to food processing, but some data indicated increases, normally of aglycones liberated from the breakdown of more complex glycosides or esters during processing. Since the native content of aglycones is usually low in foods, high RFs may occur, making general rules difficult to establish unless data on nonhydrolyzed food extracts are excluded. A few high values corresponded to increases in glycosides or derivatives that could not be produced through the breakdown of other compounds. Some inaccuracies may have been caused

Table 3. Overall changes in polyphenol content of the most studied polyphenols due to food processing, excluding data from storage processes

Compound or compound group	No. of original RFs	No. of aggregated RFs	Class and subclass	Principal foods of interest	Principal processes of interest	Retention factor (aggregated)			
						Well-defined polyphenols[a]		Grouped polyphenols[b]	
						Median	IQR	Median	IQR
Total phenolics	478	163	-	Pea, barley, potato		-	-	0.74	0.47
5-Caffeoylquinic acid	90	37	Phenolic acids, hydroxycinnamic acids	Potato, carrot, tomato	Boiled, steamed, microwaved, baked	0.81	1.45	0.38	0.40
Quercetin	71	48	Flavonoids, flavonols	Tomato, onion, broccoli	Boiled, jam making	2.34	1.40	0.64	0.47
Caffeic acid	69	36	Phenolic acids, hydroxycinnamic acids	Potato, tomato, black bean	Boiled, steamed	1.18	3.10	0.48	0.57
Quercetin 3-*O*-rutinoside	53	20	Flavonoids, flavonols	Green bean, zucchini, tomato	Boiled, dried	0.56	0.31	0.33	0.44
Ferulic acid	52	36	Phenolic acids, hydroxycinnamic acids	Tomato, maize, asparagus	Boiled, baked	1.95	1.31	0.59	0.46
p-Coumaric acid	41	24	Phenolic acids, hydroxycinnamic acids	Peanut, carrot, potato	Roasted, boiled	2.21	2.57	0.95	0.71
Gallic acid	41	19	Phenolic acids, hydroxybenzoic acids	Chestnut, bean, tomato	Boiled, roasted	0.42	1.27	0.53	0.64
Kaempferol	36	31	Flavonoids, flavonols	Strawberry juice, onion	Jam making, boiled	1.27	1.56	0.68	0.51
Sinapic acid	31	28	Phenolic acids, hydroxycinnamic acids	Onion, broccoli, strawberry juice	Boiled, steamed	0.33	1.10	0.47	0.40
Protocatechuic acid	30	18		Bean, potato, tomato	Microwaved, boiled, steamed	0.59	1.02	0.38	0.27
Anthocyanins (total)	27	12	Flavonoids	Rhubarb, red cabbage	Boiled	0.63	0.34	0.35	0.54
4-Caffeoylquinic acid	27	7	Phenolic acids, hydroxycinnamic acids	Potato	Boiled, baked	0.80	0.48	-	-
4-Hydroxybenzoic acid	23	21	Phenolic acids, hydroxybenzoic acids	Bean, strawberry	Boiled, baked	0.39	0.25	0.46	0.67
(+)-Catechin	20	8	Flavonoids, flavanols	Fig, grape	Dried	0.70	0.91	-	-
Cyanidin 3-*O*-glucoside	20	6	Flavonoids, anthocyanins	Strawberry	Jam making, pasteurized	0.67	0.20	-	-
Vanillic acid	19	15	Phenolic acids, hydroxybenzoic acids	Bean	Boiled	0.21	0.18	0.49	0.29
Pelargonidin 3-*O*-glucoside	19	5	Flavonoids, anthocyanins	Strawberry	Jam making	0.68	0.28	-	-
Capsaicin	17	11	Capsaicinoids	Pepper	Grilled	0.86	0.56	-	-
Naringenin	17	9	Flavonoids, flavanones	Tomato	Canned, pastuerized	5.26	0	0.71	0.71

a) Well-defined polyphenols from food extracts not hydrolyzed prior to processing.
b) Changes in polyphenol content measured after hydrolysis of food extracts, e.g. all derivatives of particular aglycones, grouped subclasses, or total phenolics.
RF, retention factor.

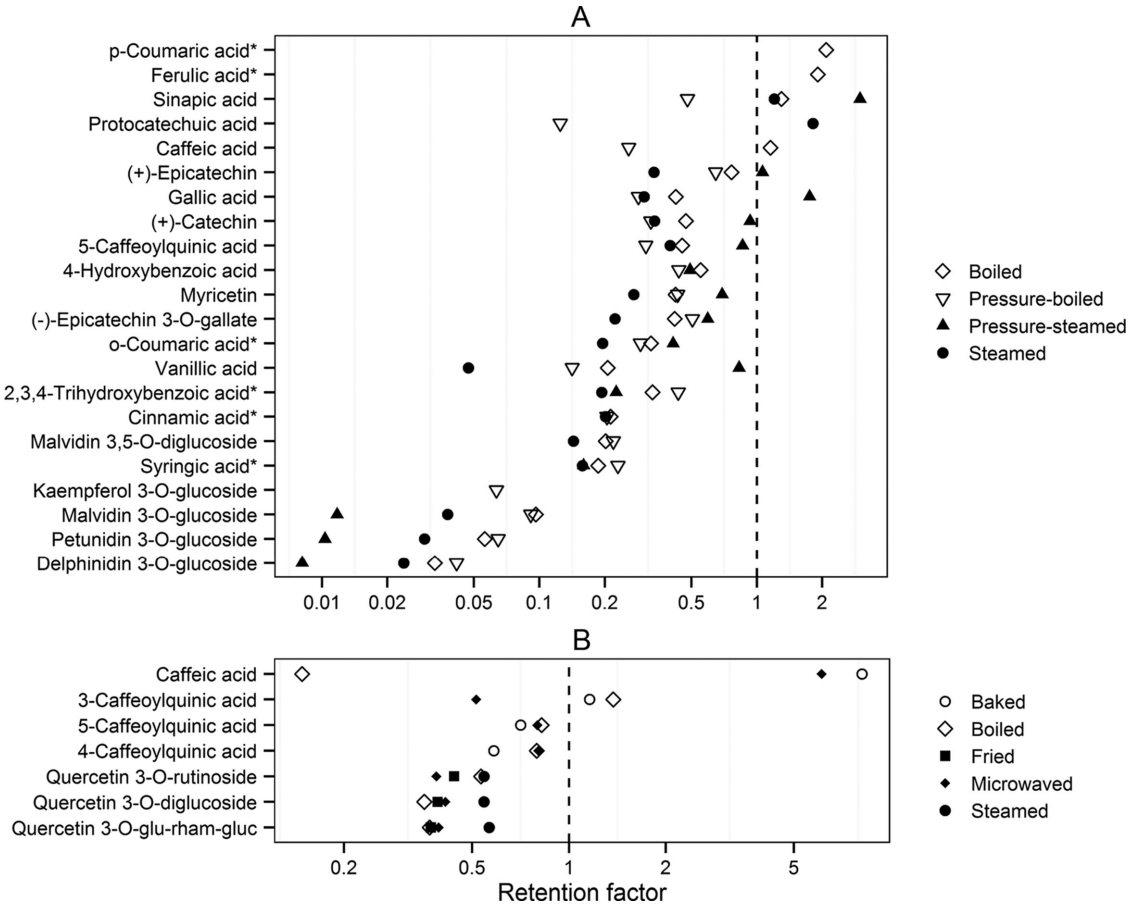

Figure 6. Retention of a range of polyphenols in (A) black bean and (B) peeled potato subject to different cooking methods. Compounds marked by asterisks were measured after hydrolysis of food extracts and may therefore represent heavier molecular weight derivatives. RFs are plotted on a log scale and polyphenol content prior to processing is indicated by the dotted line (RF = 1).

by the use of yield factors that were extrapolated where no published values were available. Also, some phenolics may also be bound to nondigestible components of the food matrix, and disruption of cellular structure by processing could cause their release and solubilization [42]. Ferulic acid, e.g. is found covalently bound to fiber in wheat bran [43].

Storage processes usually caused only minor changes in polyphenol content, although severe losses were noted in a few cases after storage at ambient temperature. Domestic and industrial processing of plant foods typically caused heavier polyphenol losses. The median RF for grouped polyphenols of both steamed and boiled data indicated that polyphenol content is typically halved due to these processes, but high variability within processes implied the importance of other variables. Variability is caused not only by polyphenol structure and food matrix, but other factors such as cooking time and temperature and piece size, which could not be accounted for in this study. In the broadest terms, no commonly used cooking method stood out as less damaging to polyphenol content than the others, and therefore these data support the observations of Miglio et al. [14] that foods must be considered individually when processing to optimize polyphenol content.

Almost all the most frequently studied foods sustained overall losses of polyphenols due to processing. Data pooled by food were less variable than data pooled by processes, although individual foods would usually correspond to a limited range of processes and polyphenols. Excluding data from storage processes, potato was the food least sensitive overall to polyphenol loss, even though it often subject to harsh processes such as boiling, as well as strawberry, which is normally subject to milder processes. Peas and beans were also frequently boiled but were considerably more sensitive than potato with much lower median RFs. Overall, polyphenol losses in carrot and broccoli were variable, with individual polyphenols lost to different extents depending on the cooking method. When subject to boiling, which would be common for these foods, both suffered considerable losses of most polyphenols, particularly of flavonol glycosides. Chemical structure strongly influences the extent of loss of individual polyphenols, and this in turn may partially explain differences between foods, since each food contains a characteristic profile of polyphenols. Since polyphenols are grouped into subclasses with common chemical backbones, it might follow that members of the same subclass are affected similarly

by food processing. However, median RFs for the most frequently studied grouped compounds were typically 0.5 or less, indicating that all subclasses of dietary polyphenols may be degraded by food processing, although RFs within subclasses were highly variable. These variations may be explained by hydroxylation pattern and bound sugars, as these determine molecular size, polarity, and solubility. The high RFs often observed for simple phenolic acids show that they often form upon degradation of more complex polyphenols.

These data should prove to be useful for refining estimations of intake in observational studies on polyphenols and health [44], and RFs should be employed in the building of food composition tables wherever experimentally determined polyphenol contents of processed foods are not available. In conclusion, this analysis of Phenol-Explorer data leads us to recommend that only published RFs matching food, process, and polyphenol be used when adjusting the polyphenol contents of raw foods to account for processing. Where this is not possible, RFs used should at least match the food and polyphenol, as process is most often less influential than these factors. For some specific process and foods, the use of prescribed values could be acceptable, such as for potato or jam-making, for which variation in Phenol-Explorer data was low. Above all, we advise against the use of limited generic RFs for many combinations of process, food, and polyphenol, and where no close RF is available, omission of the RF altogether is preferable.

This work was supported by Wereld Kanker Onderzoek Fonds (WCRF NL 2012/604) A.M.-R. acknowledges the Juan de la Cierva postdoctoral program (JCI-2012-13463) from MEC (Ministerio de Economía y Competitividad).

The authors have declared no conflict of interest.

5 References

[1] Scalbert, A., Manach, C., Morand, C., Remesy, C. et al., Dietary polyphenols and the prevention of diseases. *Crit. Rev. Food Sci. Nutr.* 2005, *45*, 287–306.

[2] Neveu, V., Perez-Jimenez, J., Vos, F., Crespy, V. et al., Phenol-Explorer: an online comprehensive database on polyphenol contents in foods. *Database* 2010, *2010*, bap024.

[3] Zamora-Ros, R., Agudo, A., Lujan-Barroso, L., Romieu, I. et al., Dietary flavonoid and lignan intake and gastric adenocarcinoma risk in the European Prospective Investigation into Cancer and Nutrition (EPIC) study. *Am. J. Clin. Nutr.* 2012, *96*, 1398–1408.

[4] Wang, Z. J., Ohnaka, K., Morita, M., Toyomura, K. et al., Dietary polyphenols and colorectal cancer risk: the Fukuoka colorectal cancer study. *World J. Gastroenterol.* 2013, *19*, 2683–2690.

[5] Rothwell, J. A., Perez-Jimenez, J., Neveu, V., Medina-Remon, A. et al., Phenol-Explorer 3.0: a major update of the Phenol-Explorer database to incorporate data on the effects of food processing on polyphenol content. *Database* 2013, bat070.

[6] Rickman, J. C., Barrett, D. M., Bruhn, C. M., Nutritional comparison of fresh, frozen and canned fruits and vegetables. Part 1. Vitamins C and B and phenolic compounds. *J. Sci. Food Agric.* 2007, *87*, 930–944.

[7] Bognár, A., Piekarski, J., Guidelines for recipe information and calculation of nutrient composition of prepared foods (dishes). *J. Food Comp. Anal.* 2000, *13*, 391–410.

[8] Amarowicz, R., Troszynska, A., Barylko-Pikielna, N., Shahidi, F., Polyphenolics extracts from legume seeds: correlations between total antioxidant activity, total phenolics content, tannins content and astringency. *J. Food Lipids* 2004, *11*, 278–286.

[9] Perez-Jimenez, J., Fezeu, L., Touvier, M., Arnault, N. et al., Dietary intake of 337 polyphenols in French adults. *Am. J. Clin. Nutr.* 2011, *93*, 1220–1228.

[10] Amarowicz, R., Carle, R., Dongowski, G., Durazzo, A. et al., Influence of postharvest processing and storage on the content of phenolic acids and flavonoids in foods. *Mol. Nutr. Food Res.* 2009, *53*(Suppl 2), S151–S183.

[11] Crozier, A., Lean, M. E. J., McDonald, M. S., Black, C., Quantitative analysis of the flavonoid content of commercial tomatoes, onions, lettuce, and celery. *J. Agric. Food Chem.* 1997, *45*, 590–595.

[12] Harnly, J. M., Doherty, R. F., Beecher, G. R., Holden, J. M. et al., Flavonoid content of US fruits, vegetables, and nuts. *J. Agric. Food Chem.* 2006, *54*, 9966–9977.

[13] Pernice, R., Parisi, M., Giordano, I., Pentangelo, A. et al., Antioxidants profile of small tomato fruits: effect of irrigation and industrial process. *Sci. Hortic.* 2010, *126*, 156–163.

[14] Miglio, C., Chiavaro, E., Visconti, A., Fogliano, V. et al., Effects of different cooking methods on nutritional and physicochemical characteristics of selected vegetables. *J. Agric. Food Chem.* 2008, *56*, 139–147.

[15] Mazzeo, T., N'Dri, D., Chiavaro, E., Visconti, A. et al., Effect of two cooking procedures on phytochemical compounds, total antioxidant capacity and colour of selected frozen vegetables. *Food Chem.* 2011, *128*, 627–633.

[16] Puuponen-Pimia, R., Hakkinen, S. T., Aarni, M., Suortti, T. et al., Blanching and long-term freezing affect various bioactive compounds of vegetables in different ways. *J. Sci. Food Agric.* 2003, *83*, 1389–1402.

[17] Ewald, C., Fjelkner-Modig, S., Johansson, K., Sjoholm, I. et al., Effect of processing on major flavonoids in processed onions, green beans, and peas. *Food Chem.* 1999, *64*, 231–235.

[18] Tudela, J. A., Cantos, E., Espin, J. C., Tomas-Barberan, F. A. et al., Induction of antioxidant flavonol biosynthesis in fresh-cut potatoes. Effect of domestic cooking. *J. Agric. Food Chem.* 2002, *50*, 5925–5931.

[19] Vallverdu-Queralt, A., Medina-Remon, A., Casals-Ribes, I., Andres-Lacueva, C. et al., Effect of tomato industrial processing on phenolic profile and hydrophilic antioxidant capacity. *Lebensm. Wiss. Technol.* 2012, *47*, 154–160.

[20] Korus, A., Lisiewska, Z., Effect of preliminary processing and method of preservation on the content of selected antioxidative compounds in kale (*Brassica oleracea* L. var. acephala) leaves. *Food Chem.* 2011, *129*, 149–154.

[21] Price, K. R., Bacon, J. R., Rhodes, M. J. C., Effect of storage and domestic processing on the content and composition of flavonol glucosides in onion (*Allium cepa*). *J. Agric. Food Chem.* 1997, *45*, 938–942.

[22] Diaz-Batalla, L., Widholm, J. M., Fahey, G. C., Castano-Tostado, E. et al., Chemical components with health implications in wild and cultivated Mexican common bean seeds (*Phaseolus vulgaris* L.). *J. Agric. Food Chem.* 2006, *54*, 2045–2052.

[23] Kuti, J. O., Konuru, H. B., Antioxidant capacity and phenolic content in leaf extracts of tree spinach (Cnidoscolus spp.). *J. Agric. Food Chem.* 2004, *52*, 117–121.

[24] Fanasca, S., Rouphael, Y., Venneria, E., Azzini, E. et al., Antioxidant properties of raw and cooked spears of green asparagus cultivars. *Int. J. Food Sci. Tech.* 2009, *44*, 1017–1023.

[25] Vallverdu-Queralt, A., Odriozola-Serrano, I., Oms-Oliu, G., Lamuela-Raventos, R. M. et al., Changes in the polyphenol profile of tomato juices processed by pulsed electric fields. *J. Agric. Food Chem.* 2012, *60*, 9667–9672.

[26] Andlauer, W., Stumpf, C., Hubert, M., Rings, A. et al., Influence of cooking process on phenolic marker compounds of vegetables. *Int. J. Vitam. Nutr. Res.* 2003, *73*, 152–159.

[27] Xu, B. J., Chang, S. K. C., Total phenolic, phenolic acid, anthocyanin, flavan-3-ol, and flavonol profiles and antioxidant properties of pinto and black beans (*Phaseolus vulgaris* L.) as affected by thermal processing. *J. Agric. Food Chem.* 2009, *57*, 4754–4764.

[28] Ferracane, R., Pellegrini, N., Visconti, A., Graziani, G. et al., Effects of different cooking methods on antioxidant profile, antioxidant capacity, and physical characteristics of artichoke. *J. Agric. Food Chem.* 2008, *56*, 8601–8608.

[29] LoScalzo, R., Fibiani, M., Mennella, G., Rotino, G. L. et al., Thermal treatment of eggplant (*Solanum melongena* L.) increases the antioxidant content and the inhibitory effect on human neutrophil burst. *J. Agric. Food Chem.* 2010, *58*, 3371–3379.

[30] Carbone, K., Giannini, B., Picchi, V., Lo Scalzo, R. et al., Phenolic composition and free radical scavenging activity of different apple varieties in relation to the cultivar, tissue type and storage. *Food Chem.* 2011, *127*, 493–500.

[31] Lutz, M., Henríquez, C., Escobar, M., Chemical composition and antioxidant properties of mature and baby artichokes (*Cynara scolymus* L.), raw and cooked. *J. Food Comp. Anal.* 2011, *24*, 49–54.

[32] Fengmei, Z., Liangbin, H., Guihua, X., Quanxian, C., Changes of some chemical substances and antioxidant capacity of mandarin orange segments during can processing. *Procedia Environ. Sci.* 2011, *11*, Part C, 1260–1266.

[33] Luthria, D. L., Pastor-Corrales, M. A., Phenolic acids content of fifteen dry edible bean (*Phaseolus vulgaris* L.) varieties. *J. Food Comp. Anal.* 2006, *19*, 205–211.

[34] Xu, X. Y., Li, W. D., Lu, Z. H., Beta, T. et al., Phenolic content, composition, antioxidant activity, and their changes during domestic cooking of potatoes. *J. Agric. Food Chem.* 2009, *57*, 10231–10238.

[35] Price, K. R., Colquhoun, I. J., Barnes, K. A., Rhodes, M. J. C., Composition and content of flavonol glycosides in green beans and their fate during processing. *J. Agric. Food Chem.* 1998, *46*, 4898–4903.

[36] Price, K. R., Casuscelli, F., Colquhoun, I. J., Rhodes, M. J. C., Composition and content of flavonol glycosides in broccoli florets (*Brassica olearacea*) and their fate during cooking. *J. Sci. Food Agric.* 1998, *77*, 468–472.

[37] Barba, A. A., Calabretti, A., d'Amore, M., Piccinelli, A. L. et al., Phenolic constituents levels in cv. Agria potato under microwave processing. *Lebensm. Wiss. Technol.* 2008, *41*, 1919–1926.

[38] Lombard, K., Peffley, E., Geoffriau, E., Thompson, L. et al., Quercetin in onion (*Allium cepa* L.) after heat-treatment simulating home preparation. *J. Food Comp. Anal.* 2005, *18*, 571–581.

[39] Rodrigues, A. S., Perez-Gregorio, M. R., Garcia-Falcon, M. S., Simal-Gandara, J., Effect of curing and cooking on flavonols and anthocyanins in traditional varieties of onion bulbs. *Food Res. Int.* 2009, *42*, 1331–1336.

[40] Makris, D. P., Rossiter, J. T., Domestic processing of onion bulbs (*Allium cepa*) and asparagus spears (*Asparagus officinalis*): effect on flavonol content and antioxidant status. *J. Agric. Food Chem.* 2001, *49*, 3216–3222.

[41] Zamora-Ros, R., Rothwell, J. A., Scalbert, A., Knaze, V. et al., Dietary intakes and food sources of phenolic acids in the European Prospective Investigation into Cancer and Nutrition (EPIC) study. *Br. J. Nutr.* 2013, *110*, 1500–1511.

[42] Acosta-Estrada, B. A., Gutierrez-Uribe, J. A., Serna-Saldivar, S. O., Bound phenolics in foods, a review. *Food Chem.* 2014, *152*, 46–55.

[43] Kroon, P. A., Faulds, C. B., Ryden, P., Robertson, J. A. et al., Release of covalently bound ferulic acid from fiber in the human colon. *J. Agric. Food Chem.* 1997, *45*, 661–667.

[44] Zamora-Ros, R., Touillaud, M., Rothwell, J. A., Romieu, I. et al., Measuring exposure to the polyphenol metabolome in observational epidemiologic studies: current tools and applications and their limits. *Am. J. Clin. Nutr.* 2014, *100*, 11–26.

