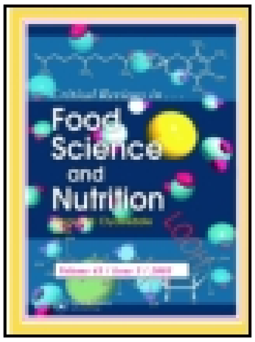

Critical Reviews in Food Science and Nutrition

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Nutrient density and bioaccessibility, and the antioxidant, satiety, glycemic, and alkalinizing potentials of fruit-based foods according to the degree of processing: a narrative review

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ABSTRACT

Epidemiological studies suggest that the protective effects of fruits against chronic diseases may vary according to their extent of processing. We therefore reviewed what the scientific literature states about the potential mechanisms underlying this "processing" effect by focusing on the most significant nutritional properties, namely, the nutritional density of bioactive compounds, the digestive bio-accessibility of nutrients, and the antioxidant, satietogenic, alkalizing and glycemic potentials. When possible, we have ranked fruits according to the international NOVA classification as un-/minimally processed, processed (mainly with added sugars), and ultra-processed fruits. Our literature review confirms that the more fruits are processed, the lower are their alkalizing, antioxidant and satietogenic potentials. For the glycemic index, the results are more difficult to interpret because fruits are a significant source of fructose with a very low glycemic index that "distorts" the "processing" effect. However, fruits in sirup tend to have a higher glycemic index, probably because of the highly bioavailable added sugars. Overall, the destructuration of the fruit fibrous matrix by thermal and mechanical treatments, combined with the addition of simple sugars, constitute the treatments that most degrade the fruit nutritive quality by diluting the nutritional density and attenuating the "matrix" effect. The new technological processes described as "nonthermal" (*e.g.*, pulsed electric fields, high pressures, supercritical CO_2, radiation, etc.) seem promising as they limit vitamin C and antioxidant phytonutrient losses in fruit while allowing satisfactory storage time. To preserve fruit longer, drying appears to be an interesting alternative to maintain the health potential of fruit, although it causes antioxidant losses. Finally, although "5 fruits and vegetables a day" is a well-known nutritional recommendation, in view of the results reviewed here, it would be relevant to be precise and include "preferably minimally processed".

KEYWORDS
Fruits; processing; nutrient density; bio-accessibility; glycemic index; satiety potential; antioxidant capacity; alkalizing potential

Introduction

Fruit products are highly varied, ranging from the least processed (fresh and dried fruits) to the most processed (fruit juice with added sugars, fruit-based sodas, ultra-processed products containing fruit preparations such as filled or coated biscuits, dairy desserts, ice cream, etc.) with intermediate transformations (100% fruit juice, canned fruit, compote, jams, etc.). However, the impact on the health of fruit products according to processing has never been systematically studied except sparsely in observational or interventional studies in humans (Fardet, Richonnet, and Mazur 2019).

In a first study, on the basis of 10 pooled analyses and meta-analyses, we have shown that there may exist a gradient of the protective effect of fruits according to the degree of processing, *i.e.*, the least processed being the most protective (Fardet et al. 2019). This tendency might be in agreement with the international NOVA classification, which ranks foods as un-/minimally processed, processed and ultra-processed, with ultra-processed products being the most deleterious for health (Monteiro et al. 2018). As previously demonstrated on 98 (Fardet 2016), 280 (Fardet et al. 2017) and 117 (Fardet, Lakhssassi, and Briffaz 2018) ready-to-eat products, the explanations behind this first global trend are probably at least three fold: 1) increased accessibility of sugars as the transformation deconstructs the matrix; 2) a low satiety potential due to a combined high sugar content and unstructured fruit matrices, generating further increased calorie intake; and 3) a deterioration of nutritional density in protective micro- and phytonutrients ("empty" calories). In addition, ultra-processed fruit drinks are richer in free sugars through added sweeteners (*e.g.*, sucrose, glucose and fructose), which might favor nonalcoholic fatty liver disease (Ouyang et al. 2008), insulin resistance (Bremer, Auinger, and Byrd 2009; Hochuli et al. 2012; McKeown et al. 2018), type 2 diabetes (Imamura et al. 2016;

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Wang et al. 2015), overweight and obesity (Ruanpeng et al. 2017). Moreover, although other studies are necessary to confirm the tendency, these results tend to show that we must favor whole fresh fruit and dried fruit, then 100% fruit juice without added sugars, and finally limit ultra-processed fruit products (Fardet et al. 2019). For canned/tinned fruit or fruits in sirup, jams and fruit purées or compotes, one cannot conclude because of a lack of studies, but it is likely that adding sugar (sucrose) or not plays an important role.

Following this first epidemiological approach to the relationship between fruit processing and the risk of chronic diseases (Fardet et al. 2019), the objective of this narrative review is to analyze in more details the influence of technological treatments on the health potential of fruit products according to the different processes, in particular with regard to the composition in bioactive micro- and phytonutrients; the glycemic, antioxidant, satiety and alkalinizing potentials; as well as the digestibility and bioaccessibility of nutrients of fruits, notably linked to the "matrix" effect (Fardet 2017; Fardet, Souchon, and Dupont 2013), to identify the least harmful processes for fruit products.

What is food health potential? a new holistic definition more in line with reality

Food health potential (FHP) cannot be defined based on only nutritional composition anymore (Fardet and Rock 2018). Two foods with different matrices and identical compositions (*e.g.*, ground *versus* whole almonds) do not have the same health effects, notably with regard to the kinetics of nutrient release within the digestive tract, impacting further metabolic effects (Fardet 2015; Fardet et al. 2013). We eat food with matrices, not nutrients. Calories and nutrients are not interchangeable from one food to another, implying, for instance, that it is not the same impact on health to consume 100 kcal from apple and 100 kcal from flavored and sweetened soft drink, representing 100 kcal of minimally processed or ultra-processed foods, respectively (Fardet and Rock 2018).

Based on recent research findings, the FHP has been redefined as a combination of both "matrix" and "composition" effects (Fardet and Rock 2018), *i.e.*, FHP = "composition" x "matrix" effects, with "composition" being the quantitative and reductionist fraction and "matrix" the holistic and qualitative fraction resulting from specific nutrient interactions. This new holistic definition of FHP has fundamental consequences for human health, notably implying that a whole food is more protective than the sum of its reconstituted nutrients.

A brief overview of the main fruit processes

Processing not only impacts food composition but also the food matrix, notably through unstructuration, refining and cracking. The modification of the fruit matrix is important because it may potentially play a role in the bioavailability of sugars, feeling of satiety and speed of digestive transit (Fardet and Rock 2018). It is therefore not harmless to health to unstructure the fruit matrix. Technologists are used to distinguishing between processes that preserve (Brat and Cuq 2007b) and those that alter (Brat and Cuq 2007a) the initial structure of fruits.

Processes that preserve the fruit matrix

In 2007, Brat and Cuq proposed a schematic representation of the different technological pathways that can be used for fruit processing while preserving the original structure (Figure 1) (Brat and Cuq 2007b). In view of the applied treatments, namely, washing, sorting, sizing, trimming (pitting, tailing and peeling), cutting, blanching (1–2 minutes in boiling water), preserving, drying and packaging, these fruit products may be predominantly considered to be minimally processed according to the NOVA classification (Monteiro et al. 2016).

Fruit conservation techniques that preserve the original structure can be grouped into five categories, as described by Brat and Cuq (2007b):

- Ready-to-use fruits, comprising products that have undergone minimal processing (direct consumption) and for which the storage conditions guarantee the quality of end-of-life products.
- Frozen fruits (without added sugars), comprising products that are preserved by the implementation of negative temperatures sufficient to block the degradation reactions; however, freezing, under the mechanical effect of the large ice crystals present in the interstices, destroys the cellular integrity of fruits because the initial rigidity of the outer cellulosic wall depends on the state of the pectic cement linked to the maturity of the fruits. Upon thawing, Brat and Cuq explained that "*the water contained in the cellular interstices causes an exudate, all the richer in soluble constituents that the process will be slow… The exudate carries with it both water-soluble vitamins, sugars and minerals. It should therefore be consumed to limit nutritional losses*" (page 12) (Brat and Cuq 2007b).
- Canned fruit, comprising products for which heat treatment has been implemented to inactivate the factors causing fruit degradation reactions (microbiological, physiological and enzymatic) and which are conditioned in packaging to prevent recontamination during storage.
- Dried fruits through thermal treatments, comprising products that have been partially dehydrated (and therefore not absolutely dry) to be stored for a long time, fabricated from fruit whose dry matter does not exceed 30% of the wet weight; this helps to lower the water activity in the fruit matrix, causing modification of the initial structure.
- Dried fruits through the dewatering-impregnation soaking process (DISP), which consists of putting in contact with the fruit, whole or fractionated, a solution that is highly concentrated in sugars, *i.e.*, (semi)candied fruits. In general, an outlet of water from the product to the

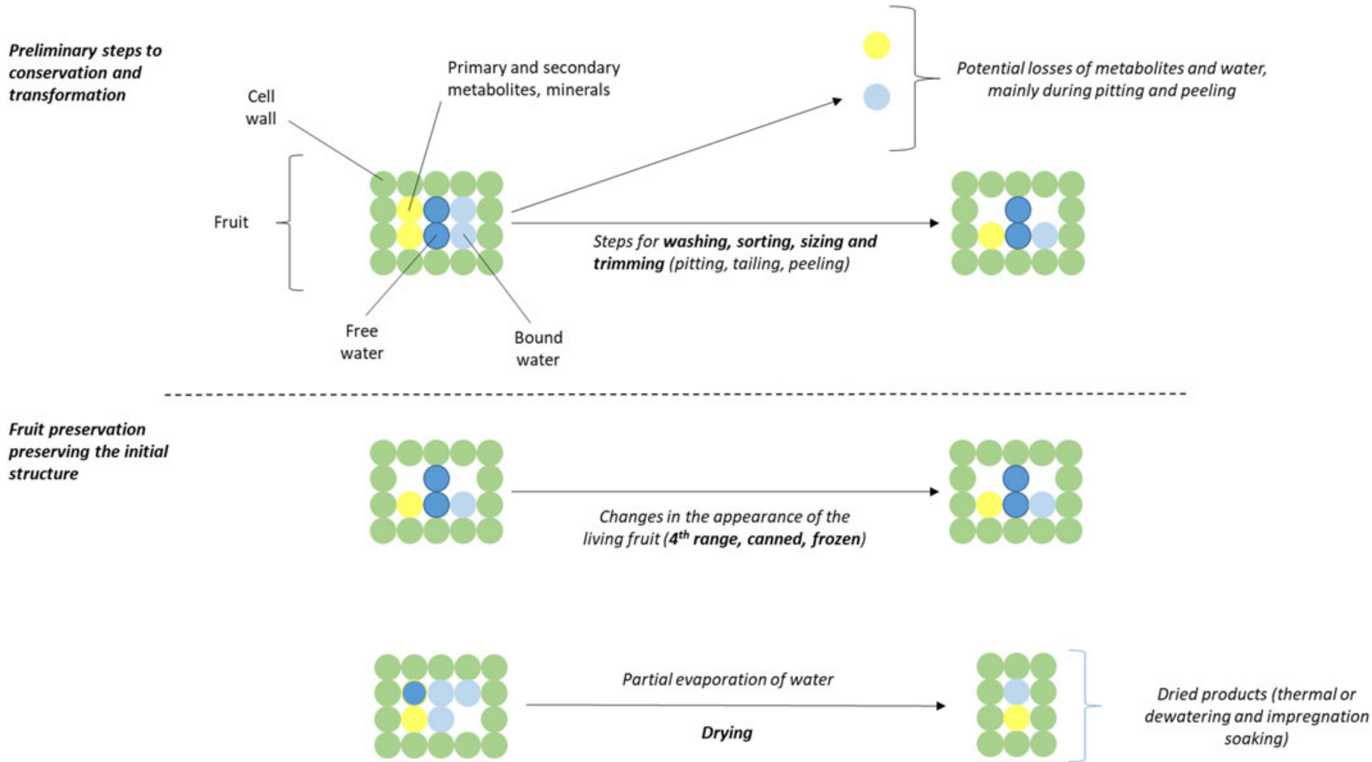

Figure 1. Schematic representation of the different technological paths that can be used to process agricultural raw materials while preserving the initial structure (reproduced from Brat and Cuq (2007b) with permission of Editions des Techniques de L'Ingénieur©).

solution and a transfer of sugar to the product in the opposite direction occur.

None of these treatments is neutral towards the initial FHP and integrity. In addition to thermal treatments, one must also mention ionizing radiation (a nonthermal process such as ionization with γ-rays, X-rays or accelerated electron beams) that allows for the destruction of microorganisms and insects and inhibition of physiological processes of germination.

Processes that alter the fruit matrix

There are three main groups of processes that alter the fruit matrix (Figure 2) (Brat and Cuq 2007a):

- Fruit preservation after extraction, separation and/or processing, which includes juices, purees, concentrates and jams.
- Fruit fermentation, which includes products such as wine and alcohols of various fruits and varieties (distilled alcohols, liquors and brandies).
- Cracking of functional elements of fruits, *e.g.*, pectins, sugars.

Fruits can be directly pressed to obtain a juice provided that the proportion of free water is high enough (Brat and Cuq 2007a). Once the juice is obtained, it is subjected, depending on the type of fruit, to different stages of enzymatic treatments before being concentrated or pasteurized as such. The average water content of the juices is approximately 88%. One distinguishes two types of fruit juices: 100% pure fruit juices obtained by simple pressing of fruits, without the addition of any sugar and/or additives, and fruit juices from concentrates, mainly from citrus fruits. The products are reconstituted by reincorporating concentrated fruit juice with the same quantity of water as that extracted during the concentration. This concentration is intended to facilitate storage and transportation. Otherwise, although not widespread, fruit juices may be preserved and stabilized with very high-pressure treatments (up to 4000 bars) instead of thermal treatments, which notably allows better preservation of nutritional properties.

As written by Brat and Cuq: "*When the free water content is naturally low in a fruit (e.g., apricot, mango, peach, …) and the content in cell walls is high, a simple pressing of the fruit does not allow, under any circumstances, a good recovery of the fruit extraction product, even after a possible liquefying treatment. A fruit puree is therefore defined as a fermentable, but unfermented, product obtained by sieving the edible portion of whole or peeled fruits without removing the juice*" (page 6) (Brat and Cuq 2007a).

From the raw purees obtained, a liquefying enzymatic treatment may be useful for future preparation of nectars (Brat and Cuq 2007a). As defined by the Official Journal of the European Communities (Directive 2001/112 du 20/12/2001), a nectar is a fermentable product, but not fermented, obtained by adding water and sugars (mainly sucrose) and/or honey to fruit puree (Légifrance 2001). Jam and its related products, such as jelly or marmalade, are the result of the gelling of fruit pectins and sugar during cooking (Brat and Cuq 2007a). Gelling occurs when the mixture cools to room temperature. Fermentation is the process in

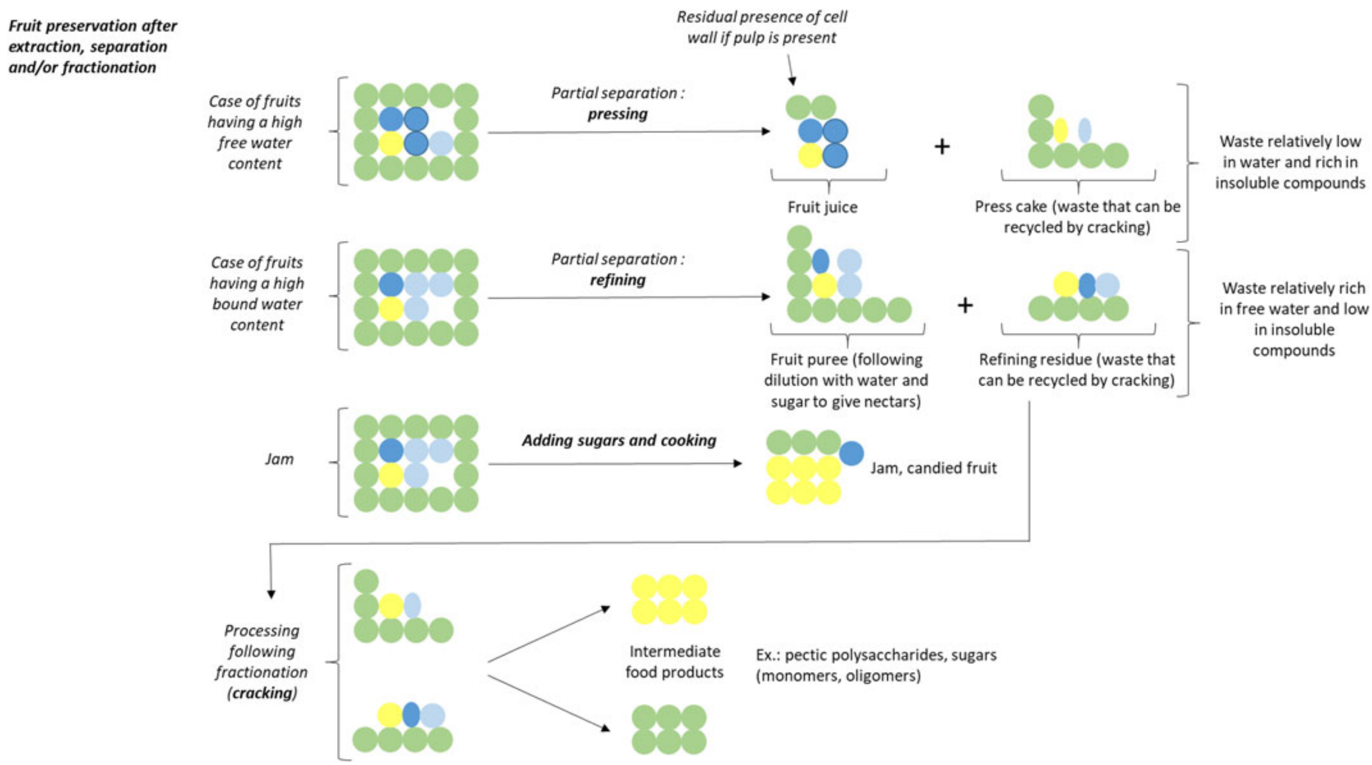

Figure 2. Various technological methods of fruit conservation (reproduced from Brat and Cuq (2007a) with permission of Editions des Techniques de L'Ingénieur©).

which sugar is converted to alcohol by yeast. Adding sugar to fruit bases will increase the alcohol levels achieved during fermentation. Once a fruit base or mash has been fermented, it can be strained to produce fruit wine or distilled to make fruit liquor.

Finally, when processing fruits as juices, purees, nectars or jams, one obtains co- or byproducts (Brat and Cuq 2007a). While coproducts are rejected fruits during the step of selection, byproducts represent products obtained during the different steps of processing (*e.g.*, skins, seeds, essential oils, in the case of citrus fruits) (Brat and Cuq 2007a). One distinguishes agropolymers such as polysaccharides and pectins, and micronutrients such as aromas and colorants (*e.g.*, carotenoid extraction with the use of supercritical CO_2).

Influence of processing on the fruit nutrient density

The influence of processing on fruit nutrient density may be studied through either nutrient databases or published peer-reviewed articles.

From the American USDA database

The most complete nutrient database for fruit-based products is the USDA (U.S. Department of Agriculture 2005). The orange and the apple, because of their frequent consumption worldwide, especially in Western countries, have been chosen as examples. The contents are expressed per 100 g of dry matter so that the comparisons are made on the same basis, with fruit-based products not having the same water content in the tables according to the process applied.

Eight orange products were compared to the whole fruit (left column) for nutrient levels (Table 1). It is interesting to focus on the protective nutrients characteristic of fruits such as fiber, minerals and vitamins. The fiber content decreases sharply after pressing the orange into 100% fresh juice, chilled juice from concentrate, canned juice, frozen concentrated juice, nectar and marmalade (divided by approximately a factor of 10). It is close to 0 in soda and Tang. The content of total minerals and total vitamins (especially vitamin C) decreases, especially for nectar, sodas, Tang© and marmalade, while juices and fruits have fairly equivalent levels.

For apple, nine products were compared to the whole fruit (left column) for nutrient content: boiled apples, compote, juice, concentrated frozen juice, canned, dried and frozen-heated apples (Table 2). As with orange, pressing strongly reduces the fiber content, while canned compote or slices keep a fiber content close to the whole apple, even if slightly lower. The total mineral content decreases after processing except for the juices. Draining apples after canning probably explains the significant loss of minerals in these products (divided by approximately two). The total vitamin content decreases much more strongly in all products compared to the whole apple, especially for drained canned apples. Undrained canned apple compote has a total vitamin content approximately six times higher than drained canned slice apples. Among vitamins, vitamin C is particularly affected.

From the French Ciqual database

Another source of data is the nutritional compositions of the foods listed in the French Ciqual database of ANSES (ANSES-Afssa 2008). One hundred thirty-eight products

Table 1. Effect of processing on nutritional composition of orange (g/100 dry weight, from (U.S. Department of Agriculture 2005)).

	Whole fruit (Florida)	Juice 100% fresh fruit	Refrigerated juice (including concentrate)	Canned juice without added sugars	Frozen concentrated juice, unsweetened, diluted	Nectar	Soda	Tang	Marmalade
Energy (Kcal)	358	385	379	382	378	360	387	367	396
Proteins (g)	5.44	5.98	6.90	5.37	5.71	2.82	0	0	0.26
Lipids (g)	1.63	1.71	2.33	1.27	0.50	0.78	0	0	0.13
Carbohydrates (g, by difference)	89.74	88.89	86.72	89.63	90.59	85.34	99.19	98.70	98.38
Fibers (g)	18,66	1.71	-[a]	1.82	1.68	1.75	0	0.30	1.70
Total sugars (g)	71.07	71.79	–	76.43	70.59	–	–	90.47	–
Total minerals (mg)	1821.18	2053.26	1925.16	1915.28	1900.78	<1133.90	170.64	739.23	<128.35
Vitamin C (mg)	349.9	427.4	368.1	313.0	326.9	205,8	0	240.7	16.0
Vitamins C + B	356.57	434.07	371.69	318.99	331.58	208.16	0	250.21	<19.90
Vitamin A (IU)	1745	1709	1258	1592	899	–	0	2006	0
α-tocopherol (mg)	1.40	0.34	–	1.82	1.68	–	–	–	0.29
Vitamin D (IU)	–	–	–	–	–	–	–	–	0
Vitamin K (*mg*)	0	0,9	–	0.9	0.8	–	–	–	1.3

aNo data.

Table 2. Effect of processing on nutritional composition of apple (g/100 dry weight, from (U.S. Department of Agriculture 2005)).

	Whole fruit (with skin)	Whole fruit (without skin), cooked, boiled	Compote, canned, unsweetened, without salt	Canned or bottled juice, unsweetened	Frozen concentrated juice, unsweetened, diluted	Canned, sweetened, sliced, drained, heated	Canned, sweetened, sliced, drained, unheated	Dried, sulfur, simmered	Dried, sulfur, uncooked	Frozen, unsweetened, heated
Energy (Kcal)	360	365	369	389	388	378	380	359	356	366
Proteins (g)	1.80	1.79	1.46	0.50	1.07	1.02	1.02	1.39	1.36	2.26
Lipids (g)	1.18	2.48	0.43	0.91	0.76	2.43	2.78	0.44	0.47	2.57
Carbohydrates (g, by difference)	95.64	93.87	96.91	96.77	88.09	95.03	94.67	96.53	96.56	93.46
Fibers (g)	16.62	16.52	10.30	0,83	0.76	11.29	9.64	12.60	12.75	14.80
Total sugars (g)	71.95	75.77	86,61	90.31	83.44	83.75	85.03	83.93	83.81	-[a]
Total minerals (mg)	901.99	801.72	794.61	1156.34	1155.08	488.32	466.32	891.71	888.77	742.86
Vitamin C (mg)	31.9	1.4	10.3	7.5	4,6	1.1	2.3	6.3	5.7	3.1
Vitamins C + B	33.56	2.87	13.29	9.42	5.76	2.09	3.25	7.95	7.83	4.33
Vitamin A (IU)	374	303	249	8	0	316	289	107	0	156
α-tocopherol (mg)	1.25	0.34	1.80	0.08	0.08	1.19	1.19	0.76	0.78	–
Vitamin D (IU)	–	–	–	–	–	–	–	–	–	–
Vitamin K (*mg*)	15.2	4.1	5.2	0	0	0	3.4	4.4	4.4	–

aNo data.

Table 3. NDS and LIM indices of fruit-based foods (n = 138) according to degree of food processing (based on NOVA classification, fruit-based alcool excluded).

Technological groups	NDS	LIM
Un-/minimally processed (n = 68)[a]	7.25	0.12
Processed (n = 28)[a]	3.49	-[b]
Complex fruit-based desserts[c] (n = 28)[a]	3.33	-[b]

[a]Number of fruit items: fruit-based food composition obtained from French Ciqual database (ANSES-Afssa 2008).
[b]No data on added sugar.
[c]Included processed (NOVA group 3) and ultra-processed (NOVA group 4) foods.

were selected as fruit products or containing a portion of fruit. The products were classified into three NOVA technological groups as previously described (Moubarac et al. 2014): un-/minimally processed (61 foods); processed (41 foods); and ultra-processed (36 foods). From their composition, the NDS (Nutrient Density Score) of these foods (Darmon et al. 2009) was calculated, and the median is given for each NOVA group (Table 3). Fruit-based products have been ranked as un-/minimally processed (raw, dried, pressed and/or cooked fruits without added sugars), processed (fruits with added sugars: canned fruits with sirup, nectars, fruit cocktail, jams and marmalades, fruit juices with added sugars), and fruit-based desserts. Due to the lack of information about ingredients/additives used in the Ciqual database for fruit-based desserts, this group may include both processed and ultra-processed foods. In addition, no data are available on added sugars, which explains why the LIM (nutrient to limit) index could not have been calculated for processed and complex fruit-based desserts.

The NDS decreases from un-/minimally processed fruits (median = 7.25) to processed fruits (3.49) and complex fruit-based desserts (3.33), mainly because of fiber and micronutrient (*i.e.*, vitamins C, E, B1, B2, B6, and B9 and calcium, iron, magnesium, zinc, and potassium) losses. As expected, the LIM index is very low in the NOVA group 1 of un-/minimally processed fruits (0.12). Fruit-based products in the processed NOVA group 3 are characterized by the addition of sugars; therefore, there is no doubt that this would have greatly increased the median LIM index to higher than that of fresh/dried fruits. If we go into detail for fruit products in NOVA group 1, we observe that fresh fruits, fruit purées and 100% fruit juices are the fruit products with the best nutritional densities (results not shown). However, from the whole fruit to the juice, the "matrix" effect is altered.

From original articles

It is difficult to study the degradation of fibers, micronutrients and phytonutrients of fruits according to the different types of technological treatments applied because a fruit product is often the result of the application of several treatments, both mechanical, thermal, and/or fermentative. Additionally, after a careful examination of the literature, it seems more relevant to present the data of the literature by type of compound:

Table 4. Average fiber content of fresh apple and applesauce (n = 8 samples) (reproduced from Colin-Henrion et al. (2009) with permission of Elsevier©).

Fiber content (g/100 g fresh weight)	Fresh whole apple	Applesauce
Fraction insoluble in alcohol	2.43 (16.20)[a]	1.76 (6.52)
Total fiber	2.33 (15.53)	1.68 (6.22)
Insoluble fiber	1.69 (11.27)	1.02 (3.78)
Soluble fiber	0.64 (4.27)	0.66 (2.44)
Soluble/Insoluble fiber	0.38	0.65

[a]Content (g) by 100 g dry weight: apple ≈ 85% water; compote ≈ 73% water.

The fiber fraction

The production of applesauce with added sugars is interesting because it involves several stages of processing. Colin-Henrion et al. included sorting (damaged products are removed), cooking, refining through a 1.2-mm filter, the addition of glucose-fructose sirup and pasteurization (Colin-Henrion et al. 2009). The total fiber content (g/100 g of fresh matter) decreased by 28% between the whole apple and the corresponding compote, notably due to the addition of sugars and the removal of the skin (refining), which is rich in insoluble fibers. As a consequence, the main decrease concerns the insoluble fiber (−40%), but the soluble fiber content is rather stable (+3%) (Table 4). As a result, the soluble/insoluble fiber ratio is almost doubled (from 0.38 to 0.65).

If we look at the different stages of processing, the total fiber content shifted from 13.9 to 11.6 g/100 g of dry matter between sorting and pasteurization, and the percentage of insoluble fibers decreased by 12% (Table 5). The largest decrease in insoluble fiber occurred at the time of refining (-10%). The effect is much less marked after approximately two months of storage in a controlled atmosphere (Batch B: see note at the bottom of Table 5). For Batch A, the increase in total fiber content after cooking is due to both soluble and insoluble fiber. For the authors, two possible explanations are "*the loss of some internal soluble materials (by dripping of the sugar solution) or a sampling bias, namely, a change in the skin/pulp/seed ratio between fresh apples and cooked apple broth*" (Colin-Henrion et al. 2009). According to the authors, during the processing of apples into applesauce, two main mechanisms can affect the fiber content: 1) heating, which leads to a depolymerization of the pectins; and 2) mechanical separation of the most resistant fractions, namely, pips, skin and carpels (Colin-Henrion et al. 2009). The soluble fiber content increases after cooking: the applied temperature (85 °C) may have contributed to the solubilization by depolymerization of the cell wall polysaccharides previously bound to the insoluble fraction, most probably the pectins. Finally, the authors mentioned the potential formation of insoluble complexes induced by the process, likely to increase the content of insoluble fibers, *i.e.*, Maillard reaction products during cooking, and the interaction of polyphenols with cell wall polysaccharides. Thus, "*the pulp/peel/seed ratio and the insoluble aggregates may have contributed to an increase in the levels of polysaccharides and insoluble fibers during cooking, more or less offsetting the loss of insoluble polysaccharide by pectic solubilization*" (Colin-Henrion et al. 2009). In conclusion, the processing of apples into applesauce represents only

Table 5. Modification of the dry matter content, the alcohol-insoluble fiber fraction, the total fiber fraction and the insoluble fiber fraction during the processing of apples into applesauce (reproduced from Colin-Henrion et al. (2009) with permission of Elsevier©).

Batch	Transformation stage	Dry matter content (g/100 g fresh weight)	Fiber content (g/100 g dry weight corrected by added sugar) Alcohol-insoluble fraction	Total fiber	(%) insoluble fiber (g/100 g)
Batch A[a]	Sorting	16.4	14.9	13.9	72
	Cooking (15 min at 85 °C)	16.0	19.1	17.4	70
	Refining (1.2 mm mesh size)	14.7	15.5	14.0	60
	Sugaring (15% of fructose-glucose sirup, 85° Brix)	16.5	12.6	12.6	57
	Pasteurization (2–3 min at 90 °C)	16.5	12.5	11.6	60
Batch B	Sorting	15.0	16.1	16.0	73
	Cooking (15 min at 85 °C)	13.9	18.2	16.7	67
	Refining (1.2 mm mesh size)	14.3	15.9	13.2	66
	Sugaring (15% of fructose-glucose sirup, 85° Brix)	15.5	13.1	13.1	52
	Pasteurization (2–3 min at 90 °C)	15.3	13.6	13.5	61

[a]Two batches, corresponding to two different storage times (beginning and end of controlled atmosphere storage).

a limited loss of dietary fiber (30%, in fresh weight) but a redistribution between the soluble and insoluble fractions. The most important changes occurred during refining and sugaring. Overall, this soluble/insoluble redistribution could affect the effects of dietary fiber *in vivo* because both types of fiber have different physiological properties, *e.g.*, insoluble fiber influences transit time and soluble fiber delays carbohydrate absorption into the blood.

In the case of pressing/extracting of fruits and the clarification of fruit juices obtained with enzymes (Sharma, Patel, and Sugandha 2017), enzymes degrade fibrous cell walls to facilitate extraction of the juice. Pressing and/or clarifying significantly reduced the dry weight fiber content in juices, up to more than 10-20 times less, as previously shown with apple and orange (Tables 1 and 2).

Carotenoids

Fruit juices are generally pasteurized to inactivate microorganisms, but this leads to losses of total carotenoids. Alternative processes have been developed, such as pulsed electric field (PEF) (Noci et al. 2008) and high pressure (HP) (Hendrickx et al. 1998). In the study by Cortes et al., PEF (30 kV/cm, 100 μs, ≈40 °C) reduced the total carotenoid content in fresh orange juice by 6.7%, while a reduction of 12.6% was reached with pasteurization (20 s at 90 °C) (Cortes et al. 2006). During storage at 2 °C, carotenoid stability was better with PEF than with fresh and pasteurized juices. In another study on orange juice, HP strongly increased the total carotenoid content by 45%, while PEF and pasteurization had no effect (Plaza et al. 2011). Following treatments, all orange juices showed good stability upon storage at 4 °C, probably due to vitamin C that protects carotenoids from oxidation, as confirmed with orange juice enriched with vitamin C (Choi, Kim, and Lee 2002) and HP orange juice (Bull et al. 2004). The better stability of carotenoids with PEF was also confirmed with other fruit juices, *i.e.*, strawberry and tomato juices (Zulueta et al. 2010).

Vitamin C

Vitamin C is an important and essential nutrient for humans and can be considered an index of the nutritional quality of processes. Vitamin C is sensitive to heat treatments. Heating, especially during pasteurization or flash pasteurization of fruit juices, is responsible for the degradation of part of the vitamin C.

Among the heat treatments, Santos & Silva synthesized the data on the retention/degradation of vitamin C in dried fruits using different methods, namely, sun, hot air, microwaves, osmotic dehydration, freeze-drying and other more marginal techniques (*e.g.*, modified atmosphere drying or low-pressure superheated steam drying) (Santos and Silva 2008). The authors conclude that it is possible that not only do the drying conditions affect the kinetics of degradation of ascorbic acid but also several other variables, including fruit characteristics (composition, shape/physical structure, water activity, pH, etc.), making the phenomenon rather complex. Vitamin C losses occur not only during the drying process but also during pre-drying treatments.

Beyond the "time x temperature" couple that affects vitamin C content, the concentration of oxygen in the drying atmosphere also influences the final content in the dried product. As reviewed by Santos & Silva, "*various authors have shown the negative effect of oxygen on the retention of vitamin C […] Consequently, the area exposed to the drying conditions is another factor that affects this nutritional parameter. Increasing the area, the food structure becomes more exposed, and degradation can be enhanced. However, depending on the relation between the area exposed and time, the degradation can be reduced since this increase tends to reduce the drying time.*" (Santos and Silva 2008).

However, the use of PEF technology at a temperature of less than or equal to 68 °C causes a lower degradation of vitamin C, especially in orange juice, compared to the degradation with thermal pasteurization (*e.g.*, 95 °C for 30 seconds) (Buckow, Ng, and Toepfl 2013). Moreover, during storage, the products treated with PEF have higher vitamin C contents than heat-treated juices, *i.e.*, strawberry, tomato and orange juices (Cortés, Esteve, and Frígola 2008; Odriozola-Serrano, Soliva-Fortuny, Gimeno-Añó, et al. 2008). In addition, a significantly higher retention of vitamin C (Elez-Martinez and Martin-Belloso 2007; Min et al. 2003; Qiu et al. 1998) was observed in orange juice treated with PEF (35 kV/cm, 59 µs, ≈60 °C) and during refrigerated storage compared to that of thermally treated orange juice (95 °C for 30 s). It should also be noted that the loss of vitamin C during storage is significantly higher than that caused by the treatment (Min, Evrendilek, and Zhang 2007; Moshonas and Shaw 1997). In general, the lower are the treatment time, the intensity of the electric field, the pulse width and the frequency, the better is the retention of vitamin C in the juices (Elez-Martinez and Martin-Belloso 2007; Isabel Odriozola-Serrano et al. 2007).

Finally, various interactions between vitamin C and ozone have been reported, notably an increase in vitamin C content (Ali, Ong, and Forney 2014; Pérez et al. 1999). This increase is likely caused by the inhibition of the activity that has been caused by ozone in several enzymes, such as ascorbate peroxidase and ascorbate oxidase (Ali, Ong, and Forney 2014). In addition, Perez et al. have also suggested that ozone stress can lead to the biosynthesis of vitamin C by using carbohydrate stores (Pérez et al. 1999). In contrast, Alothman et al. detected a decrease in the vitamin C content of pineapples, bananas and guavas treated with ozone (8 ± 0.2 ml/s, exposures for 0, 10, 20 and 30 min at an ozone generation time of 1 min) (Alothman et al. 2010). Zhang et al. concluded that higher concentrations of ozone allowed lower retention of vitamin C (Zhang et al. 2005). Therefore, the decrease in vitamin C may be caused by the induction of ascorbate oxidase activity caused by a high concentration of ozone at harmful concentrations. The vitamin C content therefore depends on the efficiency ratio of its biosynthesis and its oxidation, which can be related to the different reactions of various plants under ozone stress.

Polyphenols

There is a plethora of literature about the influence of processing on fruit polyphenol contents. It is not within the scope here to review it all. We will only propose the main conclusions.

Fruits are widely recognized as an excellent source of bioactive phenolic compounds. The important polyphenolic constituents in fruits and corresponding juices, in particular apple, pear and grape, can be divided into two groups: phenolic acids such as chlorogenic acid, and flavonoids such as quercetin or catechin. Polyphenols play important roles in the body as antioxidants and/or cellular messengers (Santangelo et al. 2007; Scalbert et al. 2002). Concerning anthocyanins, they are also a widely distributed group of phenolic compounds. Anthocyanins are natural pigments of leaves, petals and fruits that are located in the cell vacuoles, soluble in water, and range from orange-red to purple-blue in the visible spectrum. The pigments are unstable and can be degraded and discolored by many factors, such as pH, temperature, enzymes, oxygen and light. Understanding the mechanism and critical points of anthocyanin destruction by enzymatic activity might be important in the design of an extraction procedure and perhaps in the final formulation of fruit-based foods (Francis and Markakis 1989; Rossi et al. 2003).

Polyphenol yields of juices depend critically on the activity of polyphenol oxidase during processing (Spanos and Wrolstad 1992). Polyphenols degrade, oxidize or polymerize rapidly during processing (including pasteurization) and storage. Heat treatment can cause complex physical and chemical reactions affecting the phenolic composition, including the release of phenolic compounds from their bound forms and the degradation and transformation of phenolic compounds (Nagy, Rouseff, and Lee 1989). Therefore, "*the total content of phenolic compounds could be one of the most important indicators of the quality of fruit juices*" (page 981) (Chen, Yu, and Rupasinghe 2013). A higher temperature is more effective at controlling bacterial growth; however, it also leads to a greater reduction of phenolic compounds in the juice (Noci et al. 2008). Otherwise, Chen et al. also reported that the duration of treatment is also an important factor affecting phenolic degradation in the juices (Chen et al. 2013), as shown with strawberry juice (Odriozola-Serrano, Soliva-Fortuny, and Martín-Belloso 2008b). However, it has been shown that PEF treatment can achieve an equivalent microbial inactivation efficiency as thermal pasteurization but with much lower phenolic degradation. Therefore, PEF treatment can retain higher levels of phenolic compounds in fruit juices and improve their stability during storage (Buckow et al. 2013; Odriozola-Serrano et al. 2008b; Puértolas, Hernández-Orte, Sladaña, Álvarez, and Raso 2010). For detailed data on the degradation of polyphenols by pasteurization or the use of PEF, see the review by Chen et al. (Chen et al. 2013). Otherwise, numerous studies have shown that applications of UV-B irradiation to fruits, such as blueberries (Eichholz et al. 2011) and blackcurrants (Huyskens-Keil, Eichholz, Kroh, and Rohn 2007), may increase the levels of total soluble phenolic compounds in treated products. Finally, published results on the impact of ozone on polyphenol contents are contradictory, with both increased (Ali et al. 2014; Alothman et al. 2010) and decreased (Alothman et al. 2010) contents according to fruit types.

For anthocyanins, it is apparent that their increased retention in fruit following bleaching is attributed to two main factors: the reduction of enzyme-induced anthocyanin degradation, *i.e.*, complete inactivation of native polyphenoloxidase through bleaching, and higher extraction yield related to increased skin permeability of the fruit caused by heat treatment (Kalt, McDonald, and Donner 2000). This has been notably observed on unbleached *versus* bleached blueberry (Lee, Durst, and Wrolstad 2002; Rossi et al. 2003; Skrede, Wrolstad, and Durst 2000) and its juice (Rossi et al. 2003). However, bleaching alone or in combination with pasteurization has reduced the anthocyanin content of blueberry puree in another study (Brownmiller, Howard, and Prior 2008). At high temperature, the anthocyanin structure is opened to form chalcone, which then degrades into browning products (Francis and Markakis 1989). Other researchers also reported in strawberries and blackberries that the degradation of anthocyanins in concentrates was greater than that of juices (Patras, Brunton, Da Pieve, and Butler 2009). However, in strawberry juice treated with PEF, the anthocyanin content significantly depends on the treatment time (I. Odriozola-Serrano, Soliva-Fortuny, Gimeno-Añó, et al. 2008). Altuntas et al. further demonstrated that the total stability of anthocyanins in Morello cherries was well preserved after PEF treatment (17–30 kV/cm for 131 ms) (Altuntas et al. 2010), whereas PEF induces a significant loss of cyanidin-3-glucoside in blood oranges and blackberries, and degradation increases as the electric field increases (Zhang et al. 2007). These changes in anthocyanin levels during the shelf life of PEF-treated juices are probably related to the presence of residual enzymatic activities such as β-glucosidase (Aguiló-Aguayo et al. 2010).

However, reports regarding the effects of ozone on the anthocyanin content are still limited and controversial (Alexandre, Brandao, and Silva 2012; Barth et al. 1995; Pérez et al. 1999). The degradation of anthocyanins is the result of the high oxidation potential of ozone. The effects of irradiation on anthocyanin pigments depend to some extent on the nature of the anthocyanin. For example, diglycosides are relatively stable with respect to monoglycosides *vis-à-vis* irradiation (Arjeh, Barzegar, and Sahari 2015). Otherwise, water activity is another important factor influencing the stability of anthocyanins during storage (Brønum-Hansen and Flink 1985; Markaris, Livingston, and Fellers 1957). In addition, the presence of oxygen can accelerate the degradation of anthocyanins, either by a direct oxidation mechanism and/or by the action of oxidizing enzymes (Jackman, Yada, and Tung 1987). Beyond enzymatic residual activity, anthocyanin losses in fruits may also be attributed to condensation reactions of anthocyanins with other phenolic compounds (Brownmiller et al. 2008; Chaovanalikit and Wrolstad 2004; A. Hager et al. 2008; T. J. Hager, Howard, and Prior 2008; Ngo, Wrolstad, and Zhao 2007). Overall, greater anthocyanin stability can be achieved by using a lower temperature and short-term heating during processing and storage (Krifi and Metche 2000; Rodriguez-Saona, Giusti, and Wrolstad 1999).

Influence of processing on the *in vitro* fruit nutrient bioaccessibility

Bio-accessibility is defined as the amount of a component that is released from the food matrix in the gastrointestinal tract and therefore available for absorption (Parada and Aguilera 2007). It is usually measured *in vitro* with artificial digesters. Overall, many studies compare the bio-accessibility of fruit nutrients to each other (depending on the fruit type), but fewer studies have focused on studying the influence of technological processes on the bio-accessibility of bioactive compounds by comparing treated *versus* untreated fruit.

Thermal treatments

Thermal treatment can influence the phytonutrient abundance and the formation of degradation compounds, and has implications for the subsequent bio-accessibility of bioactive compounds by affecting the fruit matrix and its microstructure (Barba et al. 2017). Heat treatment may damage the cell walls, making the compounds more accessible for absorption (Barba et al. 2017). There is evidence of positive effects following heat treatments, such as better accessibility of nutrients and/or increased extractability of bioactive compounds (Barba et al. 2017), *e.g.*, with carotenoids (Fernandez-Garcia, Rincon, and Perez-Galvez 2008).

In their review, Barba et al. reported the influence of different thermal and nonthermal treatments on the bio-accessibility of various hydrophilic and lipophilic bioactive compounds in vitro (Table 6) (Barba et al. 2017). There is a trend towards increasing bio-accessibility with PEF and ultrasound and contrasting effects with HP, while heat treatments have different effects depending on the compounds considered. However, Barba et al. did not analyze all available studies (Barba et al. 2017). So, here is a brief review of what the other studies report according to various technological treatments:

Pasteurization

In a study by Aschoff et al., the *in vitro* bio-accessibility of various bioactive compounds of fresh, pasteurized or flash-pasteurized orange juice was measured (Aschoff et al. 2015). The highest concentrations of bio-accessible carotenoids were observed in pasteurized and flash pasteurized juices. The bio-accessibility of all carotenoids was significantly higher in pasteurized juices (37.6 to 39.5%) than in freshly squeezed juices (28.3%) (Aschoff et al. 2015). The heat treatment and finishing (filtering) of the fresh juice increase the bio-accessibility of lutein, β-cryptoxanthin, α-carotene, and β-carotene, while the bio-accessibility of (9Z)-antheraxanthin/zeaxanthin decreased from 35% to 17% and 16% in pasteurized and flash pasteurized juices, respectively (Aschoff et al. 2015). According to the authors, "*The insignificant change in carotenoid bio-accessibility from the flash pasteurized to the pasteurized juice indicates a "saturation" of these processing effects, meaning that further heating or finishing beyond such an "optimum processing" does not further improve carotenoid bio-accessibility*" (page 584).

In comparison with this study, Stinco et al. reported a higher relative uptake of carotenoid from *in vitro* digests in industrially pressed and finished juice (up to 52%) than in freshly squeezed juice (34%) and pasteurized industrial juice (40%) (Stinco et al. 2012). According to their study, juice finishing causes a reduction in particle size, thus improving the release of carotenoids, while thermal pasteurization apparently decreased the release of carotenoids during digestion. In contrast, the production of pasteurized orange juice significantly increases the stability of vitamin C during digestion, generating a residual level of 78% compared to that of the test food: approximately 70% for fresh and flash-pasteurized juices. Finally, no difference was observed in the bio-accessibility of flavonoids for the three juices.

Freezing, freeze-drying, microwaves and drying

In the study by Dalmau et al., *in vitro* gastric digestion of fresh, frozen (−196 °C in liquid nitrogen), lyophilized (-50 °C and 30 Pa) and convection dried (60 °C and 2 m/s) Granny Smith apples was followed (Dalmau et al. 2017). First, compared to unprocessed apples, the microstructure and composition of apples changed with all treatments, leading to behavioral changes during gastric digestion, *e.g*, faster decreases in soluble solids. Freezing and lyophilization led to decrease in the polyphenol content and antioxidant activity of apples before and during gastric digestion. Conversely, convective drying increased the initial polyphenol content and antioxidant activity of apples, but they decreased during gastric digestion. On the contrary, raw apples showed minor decreases in total polyphenol content and antioxidant activity during gastric digestion, and greater retention of polyphenols and antioxidants (Dalmau, et al. 2017).

As an alternative to conventional heat treatments such as pasteurization, which can destroy some vitamin C and alter sensory or organoleptic properties, ultra-freezing (direct immersion in liquid nitrogen) can be a less damaging alternative treatment. Stinco et al. therefore investigated different thawing methods (microwaves, refrigeration, and room temperature) of ultra-frozen orange juice on the levels and bio-accessibility of carotenoids and antioxidant activity (Stinco et al. 2013). Briefly, microwave thawing significantly affected the carotenoid content and antioxidant activity, and led to the highest relative bio-accessibility percentages for carotenoids with provitamin A activity compared to those of the other thawing methods.

In the last study by Kamiloglu et al., to evaluate the *in vitro* bio-accessibility of fresh and sun-dried figs, the total antioxidant capacity, the total pro-anthocyanidin content and the main phenolic compounds were determined at different phases of simulated gastrointestinal digestion (Kamiloglu and Capanoglu 2013). The main results showed that dried figs had increased bio-accessibility of proanthocyanidins and chlorogenic acid as well as antioxidant capacity. In addition, the bio-accessibility of anthocyanins decreases with sun-drying.

According to Ryan and Prescott, "*pasteurization can potentially increase antioxidant capacity by causing slight changes in the structure of the antioxidant compounds, which in turn makes them more stable to pH change, allowing the antioxidant activity to continue increasing after the gastric phase of the in vitro digestion process*" (page 1195) (Ryan and Prescott 2010). This theory comes from Cevallos-Casals and Cisneros-Zevallos (2004) and Kammerer et al. (2004) who found that acylated anthocyanins were more stable to pH and temperature changes. In addition, the antioxidant activity appears stabilized by boiling, probably because of the inactivation of prooxidant enzymes at elevated temperatures (Gazzani et al. 1998).

Nonthermal treatments

According to Barba et al., nonthermal treatments can be used as tools to facilitate the release of micronutrients and bioactive compounds from the plant matrix during the digestion process (Table 6) (Barba et al. 2017):

Mechanical: pressing for juices, purées and nectars

The first study compares the bio-accessibility of bioactive compounds of orange or mandarin pulp/juice (De Ancos et al. 2017). The bio-accessibility of the bioactive compounds (hesperidin, narirutin, total flavonoids, total phenols and ascorbic acid) and the antioxidant activity of the bio-accessible fraction were higher in the pulp of oranges and mandarin than those in the corresponding juices. Thus, according to the authors, the consumption of pulp compared to the same portion of fruit juice would confer a better supply of bioactive compounds and antioxidant activity (De Ancos et al. 2017). In another study, Rodrogo et al. showed conflicting results according to citrus type (Rodrigo et al. 2015). Thus, in *Navel Cara Cara* orange, bioactive carotenoids in freshly hand-squeezed juice exhibited a higher relative bio-accessibility than in pulp, while the opposite was observed for Clementine mandarins, especially for β-cryptoxanthin.

In another study with citrus fruits, the concentrations of all carotenoids (lutein, zeaxanthin, zeinoxanthine, β-cryptoxanthin) in supernatants and micelles were higher after *in vitro* digestion for orange juice compared to concentrations in un-pressed fresh fruit (Aschoff et al. 2015a). In addition, the bio-accessibility of the total carotenoids is 6.3% and 27.5%, and the bio-accessibility of β-cryptoxanthin is 4.9% and 25.9% for the orange and the corresponding juice, respectively. The same research team then studied the *in vitro* bio-accessibility of carotenoids, flavonoids and vitamin C from segments of orange, a mashed orange homogenate, the corresponding juice (pressed by hand) and then pasteurized or flash-pasteurized (Aschoff et al. 2015b). The presence of a fibrous matrix during *in vitro* digestion was assumed to significantly reduce the total bio-accessibility of all carotenoids of fresh fruit (12%) compared to juices (29–30%). However, the mechanical destructuration of orange segments in the mash before digestion did not alter the bio-accessibility of the carotenoids. The differences are even more pronounced for total flavonoids since nearly 90% is bio-accessible in juices, and only approximately 20% is in segments or homogenates of orange. For vitamin C, juice pressing increases its bio-accessibility from approximately 55–70%.

In a completely different way, an *in vitro* simulation of human digestion and uptake was applied to sour cherry and corresponding nectar (Toydemir et al. 2013). The main finding of this work is that recovery of total anthocyanins obtained from the dialyzable fraction of the nectar sample is five times higher on a fresh weight basis (13 times on a dry weight basis) than recovery obtained for the dialyzable fraction of the fruit sample, that could be related to greater anthocyanin stability in the nectar matrix (Toydemir et al. 2013). The nectar samples in this study contain more than 50% added sucrose, and high fruit sugar concentrations have been reported to maintain and stabilize anthocyanins (Wrolstad et al. 1990).

Finally, Ryan and Prescott studied the evolution of the antioxidant potential of fruit juices (15 fresh and 10 from concentrates with a long shelf life) before and after *in vitro* digestion (Ryan and Prescott 2010). Overall, for many of the juices, the total antioxidant capacity was significantly increased after *in vitro* digestion. A possible explanation is that the heat treatment destroys the cell wall, allowing more antioxidant components to be released, and resulting in

Table 6. Impact of thermal and non-thermal treatments on the bioaccessibility of lipophilic and hydrophilic compounds in fruit products (adapted from Barba et al. (2017) with permission of Elsevier©).

Technological treatments and parameters	Fruit matrix	Bioactive compound	Effet on bio-accessibility	Reference
Thermal treatments				
Pasteurization (97 °C/30 s)	Kiwifruit puree	Lutein, neo-lutein, β-carotene, neoxanthin, violaxanthine	No effect	Benlloch-Tinoco et al. (2015)
Heating (90 °C/30 s)	Fruit drinks with milk and soy	β-carotene, β-cryptoxanthin, zeinoxanthine, lutein and total carotenoids	↓	Cilla et al. (2012)
Heating (90 °C/30 s)	Fruit drinks with milk	Calcium Phosphorus	Skimmed milk: ↑ Whole milk: ↓ Skimmed milk: ↓ Whole milk: ↓	A. Cilla et al. (2011)
Steam cooking	Blueberry compote	Anthocyanes	↑	Del Bo' et al. (2012)
Microwaves (1000 W, 340 s)	Kiwifruit compote	Lutein, neo-lutein, β-carotene, neoxanthin, violaxanthine	No effect	Benlloch-Tinoco et al. (2015)
Non thermal treatment				
High pressures (400 MPa, 40 °C, 5 min)	Fruit drinks with milk and soy (orange, kiwi, pineapple and mango)	Total carotenoids	Higher vs heat treatments Lowest vs untreated	Cilla et al. (2012)
High pressures (400 MPa, 40 °C, 5 min)	Fruit drinks with milk	Calcium Phosphorus	Skimmed milk: ↑ Whole milk: No effect Skimmed milk: No effect Whole milk: No effect	A. Cilla et al. (2011)
High pressures (400 MPa, 40 °C, 5 min)	Fruit drinks with milk and soy	α-tocopherol, γ-tocopherol et δ-tocopherol	No effect (α-tocopherol) ↓ (γ- et δ-tocopherol)	Cilla et al. (2012)
Homogenization at high pressures (250 MPa/10 min)	Orange, grape or apple + soya juice, whole or skimmed milk	Phenolic compounds	No effect for orange juice or raisin + soy or whole milk or skim ↑ for apple juice + soy milk	He et al. (2016)
Pulsed electric fields (35 kV/cm, 4 μs bipolar pulses, 200 Hz, 1800 μs)	Blend of fruit juice (orange, kiwi, pineapple and mango) combined with water or milk or soymilk after application of pulsed electric field	*cis*-violaxanthin + neoxanthin	↑	Rodriguez-Roque et al. (2016)
Pulsed electric fields (25 kV/cm, 50-400 pulses)	Blend of fruit juice (50.75% (v/v) papaya, 19.25% (v/v) mango) combined with 30% (v/v) infusion of Stevia rebaudiana (2.5%, p/v)	Total carotenoids	↑	Buniowska et al. (2017)
Pulsed electric fields (25 kV/cm, 50-400 pulses)	Blend of fruit juice (50.75% (v/v) papaya, 19.25% (v/v) mango) combined with 30% (v/v) infusion of Stevia rebaudiana (2.5%, p/v)	Vitamin C and phenolic compounds	Ascorbic acid not detected following intestinal digestion Phenolic compounds and anthocyanins Total carotenoids	Buniowska et al. (2017)
Pulsed electric fields (35 kV/cm, bipolar pulses width 4 μs at 200 Hz during 1800 μs)	Beverages based on fruit juice	Vitamin C and phenolic compounds	↑	Rodriguez-Roque et al. (2015)
Ultrasounds (400 W and 24 kHz, 20-160 s)	Blend of fruit juice (50.75% (v/v) papaya, 19.25% (v/v) mango) combined with 30% (v / v) infusion of Stevia rebaudiana (2.5%, p/v)	Total carotenoids	↑	Buniowska et al. (2017)
Ultrasounds (400 W and 24 kHz, 20-160 s)	Blend of fruit juice (50.75% (v/v) papaya, 19.25% (v/v) mango) combined with 30% (v/v) infusion of Stevia rebaudiana (2.5%, p/v)	Vitamin C and phenolic compounds	↑ phenolic compounds and anthocyanins. Ascorbic acid not detected following intestinal digestion ↑ Total carotenoids	Buniowska et al. (2017)

a greater antioxidant capacity (Dewanto, Wu, and Liu 2002; Dewanto et al. 2002; Jeong et al. 2004; Takeda et al. 2003).

High pressure

Briones-Labarca et al. studied the effect of HHP on the bioaccessibility of specific nutrients (antioxidants, minerals and starch) in apple and established the conditions of the process that maximize health benefits (Briones-Labarca et al. 2011). The apple was pressurized at 500 MPa for 2, 4, 8 and 10 minutes. The antioxidant potential of the apple increases during digestion and with the duration of the application of HHP. It is possible that changes in the matrix of fibrous tissues induced by HHP, for example, cell wall destructuring, resulted in the release of compounds with antioxidant action (Briones-Labarca et al. 2011). The HHP also increased the available contents in the apple before digestion from 2% (500 MPa/10 min) to 303% (500 MPa/8 min) for calcium, 5–11% for iron and 9–29% for zinc depending on the application time. However, the dialyzability and solubility of calcium, iron and zinc, compared to the values of untreated apples, were reduced by HHP. According to the authors, "*This indicates that the bio-accessibility of these minerals, especially calcium, is not necessarily dependent on its concentration in the apple*" (page 526). In addition, the digestible starch fraction increases with the duration of application of HHP.

In conclusion, Barba et al. (77) recalled, "*The action of HP is based on a decrease in molecular volume changes, which may induce chemical reactions and physical transformations. This compression of the volume seems to be highly effective in modifying the integrity of cell walls and membranes (*Patterson 2014*), thus promoting the extractability of the intracellular bioactive compound and facilitating its solubilization" (Barba et al.* 2017*). "Thus, it is likely that HP facilitates the release of lipophilic compounds through plant cell disruption, resulting in increased bio-accessibility of carotenoids"*. They concluded that, "*the type and strength of the cell wall depend on the type of fruit and vegetables, and in turn the pressure-induced cell disruption depends on the pressure level and may be the reason for the different results reported on bio-accessibility of carotenoids*" (Barba et al. 2017).

Pulsed electric fields

The studies reported by Rodríguez-Roque et al. (2016) and Buniowska et al. (2017) showed that the transformation of fruit juices by PEF positively affects the bio-accessibility of carotenoids (Table 6). Since considerable cell disruption is expected due to chopping and pressing of the fruits, the increase is apparently obtained by improvements induced by PEF in the enzymatic activity.

In their review, Barba *et al.* explained that the phenomenon of electroporation, a direct consequence of an electrical "break", could be the main factor responsible for the modification of bio-accessibility (Barba et al. 2017). This phenomenon allows the perforation of the cytoplasmic membrane, favoring the escape of the cellular contents and probably the solubilization and digestion.

Ultrasound

The effects of ultrasound have not been extensively studied. Basically, ultrasound yields microbubbles (in the liquid) that develop but finally collapse, favoring the formation of shock waves (Barba et al. 2017). These shock waves generate high temperatures and pressures leading to cavitation, which affects cell walls and membranes (Cravotto and Binello 2016). As reviewed by Barba et al. (2017), ultrasound promotes cell wall disruption, facilitating, for example, the release of bound carotenoids or the extractability of carotenoids by promoting the breakdown of the carotenoid-protein binding (Buniowska et al. 2017; Cravotto and Binello 2016).

Storage and ripening

The storage of fruits, and therefore ripening during this period, can influence the bio-accessible fractions of bioactive compounds, as evidenced by the following studies:

Mandarin storage for 5 weeks at 12 °C increases the bio-accessibility of bioactive compounds (ascorbic acid, phenolic acids and total flavonoids) (De Ancos et al. 2017). Similarly, Schulz et al. showed that acai berries (or *Juçara*) had higher antioxidant activity after digestion, and increased bio-accessibility of various phenolic and flavonoid acids between 42 and 69 days of ripening after red berries appeared on the branches (Schulz et al. 2017).

For starch-rich bananas, the degree of ripening plays an important role in the bio-accessibility and digestibility of starch to glucose. Vatanasuchart et al. compared the hydrolysis indexes of three varieties of banana at different stages of maturity: green, yellow-green and ripe bananas (Vatanasuchart, Butsuwan, and Narasri 2015). The results are contradictory: while one variety (*Mali-ong*) has a slightly lower *in vitro* hydrolysis index for ripe banana compared to that of green banana, the opposite is observed for the other two varieties (*Khao-nuan* and *Laong-nam*).

Cilla et al. have also shown that cold storage (2-4 °C) for 135 days of fruit juice made from orange and grape concentrates and apricot puree (with added sucrose) increases the antioxidant capacity in the course of gastrointestinal digestion *in vitro* (+ 20-59%) (Antonio Cilla et al. 2011). According to the authors, "*this improvement in antioxidant capacity could be explained, at least in part, by the release of bound antioxidants (mainly polyphenols) from the food matrix by the action of digestive enzymes in the small intestine*" (page 91).

Finally, Ornelas-Paz et al. were interested in the impact of the mango ripening stage (light, moderate and complete) on the *in vitro* bio-accessibility of β-carotene (Ornelas-Paz et al. 2008). The authors reported that the amount of β-carotene transferred to the micellar fraction during simulated digestion increased significantly as the fruit ripened, probably due to qualitative and quantitative changes that occur in pectin from mango pulp during ripening, and that influenced micellarization of β-carotene.

Influence of processing on the fruit antioxidant potential

In vitro

Antioxidant levels of fruit products have been reported by Carlsen et al. among more than 3100 foods and food ingredients (Carlsen et al. 2010). These tables are the most complete to date, and they give values for different degrees of fruit processing (Table 7). Based on median values, plant products are on average 9 times richer in antioxidants than animal products. Among plant products, fruits are a significant source of antioxidants, especially given their high-water content. Among fruits, berries are the richest in antioxidants, with a maximum of 34.5 mmol/100 g for dog rose berries. Regarding the influence of processing, fruit and juices have similar median values of 0.7–0.8 mmol/100 g. Drying increases the antioxidant content with a median value of 2.4 mmol/100 g, mainly due to the loss of water. Canned fruits have a fairly high median antioxidant content of 2.0 mmol/100 g. One of the possible explanations is that the appertisation releases antioxidant polyphenolic molecules (the bound forms become free) within the fruits, making them accessible to the assays. Despite refining, due to the loss of water, jams have a higher median value than fresh

Table 7. Median antioxidant content of different fruit products acccording to the degree of processing (adapted from Carlsen et al. (2010)).

	Antioxidant content (mmol/100 g)
Plant-based products	0.9 (n = 1943)
Animal-based products	0.1 (n = 211)
Plant- and animal-based products	0.3 (n = 854)
Berries and derived products	9.9 (n = 119)
Fruits and fruit juices	1.3 (n = 278)
Fresh fruits	0.8 (n = 40)
Dried fruits	2.4 (n = 17)
Fruit juices	0.7 (n = 10)
Canned fruits	2.0 (n = 7)
Jams	1.1 (n = 4)
Red wine	2.5 (n = 1)
White wine	0.3 (n = 1)
Fruit sirups	2.4 (n = 4)
Fruit-base sweetened beverages	0.1 (n = 13)
Mango sorbet	0.1 (n = 1)

fruit, *i.e.*, 1.1 mmol/100 g. Fruit sirups also concentrate antioxidants to a median value of 2.4 mmol/100 g. Fermentation of grapes into red and white wine gives a median antioxidant content of 1.4 mmol/100 g, similar to that of fresh grapes. Finally, sweetened fruit-based beverages have the lowest antioxidant levels, *i.e.*, 0.1 mmol/100 g.

Other authors have measured the antioxidant potential of fruit products, especially for different fresh fruits (Li et al. 2011; Miller et al. 2000; Pellegrini et al. 2006); however, the use of different chemicals for the antioxidant assays makes it difficult to compare with the exhaustive and systematic study of Carlsen et al. (2010). Pellegrini et al. showed that among the dried fruits tested in their study, prunes have the highest antioxidant potential (Pellegrini et al. 2006), in agreement with the more recent study by Chang et al. (Chang, Alasalvar, and Shahidi 2016). Miller et al. confirmed that berries are much richer in antioxidants than other fruits by +68% (Miller et al. 2000). Among fruits other than berries, they also report that plums are 22 times richer in antioxidants than watermelons – the least rich (Miller et al. 2000) – which is very close to the results of Carlsen et al. (20 times richer) (Carlsen et al. 2010). For Li et al., pomegranate, plum and guava are among the richest antioxidant fruits, berries aside, and the antioxidant capacities of the 62 fruits tested are significantly correlated with polyphenol levels (Li et al. 2011). This significant correlation was also shown for 18 nontraditional tropical fruits from Brazil (Rufino et al. 2010), 11 more traditional fruits (Sun et al. 2002), and for different fruit juices (n = 36) (Borges, Mullen, and Crozier 2010), but not more than 9% for citrus-type traditional fruits (Sun et al. 2002), probably because vitamin C could importantly contribute to the antioxidant potential. This correlation is also found between the polyphenol concentration and antioxidant potential of several applesauces (Oszmianski et al. 2008). More generally, the vitamin C content of fruits is not very significantly correlated with the antioxidant potential (Proteggente et al. 2002). Finally, Wang *et al.* calculated that most of the antioxidant capacity of fruits comes from the juice fraction and that the contribution of the fruit's pulp fraction to the total antioxidant activity of a fruit is generally less than 10% (Wang, Cao, and Prior 1996).

Various studies have reported antioxidant activities of dried fruits (*e.g.*, peaches and dates), which are always higher than those of their corresponding fresh equivalents (Ishiwata et al. 2004; Rababah, Ereifej, and Howard 2005; Threlfall, Morris, and Meullenet 2007; Vinson et al. 2005), obviously because antioxidants are concentrated after the dehydration process, as has been shown with six fresh and dried fruits (apricot, plum, cranberry, grape, fig and date) (Vinson et al. 2005). However, on a dry matter basis, the drying process can significantly reduce the polyphenol content in the fruit (Vinson et al. 2005). For dried fruits, hydrophilic antioxidants account for more than 94% of the total antioxidant activity (Wu et al. 2004). However, dried fruits have a higher antioxidant potential than vitamins E and C taken alone (Vinson et al. 2005).

Otherwise, the influence of thermal (cooking, bleaching, drying, osmotic dehydration, and extrusion-cooking) and nonthermal (PEF, radiation, dense phase carbon dioxide, ozone, and edible coating) treatments on fruit antioxidant potentials has been extensively and comprehensively studied in several other specific and original articles. We cannot review all of them here. A good summary of the effect of nonthermal treatments can be found in the review by Xue et al. (2016).

The results of these studies are very complex, sometimes with seemingly contradictory data that may be due to variation in different factors: (i) type, variety and degree of maturity of the fruit; (ii) number of technological treatments undergone (thermal, nonthermal, mechanical, additions of ingredients and/or additives, etc.) each with a particular action on each antioxidant (hydrophilic and lipophilic); (iii) variation of the parameters for the same treatment (pressure, temperature, duration, concentrations, etc.); (iv) various antioxidant tests used; and (v) generation, at the same time as degradation, of antioxidant compounds during certain treatments. Table 8 summarizes the effects (trends) of the different technological treatments applied to the fruits on the antioxidant potential. In their review dedicated to the effects of processing on the phenolic antioxidants of fruits and vegetables, Nayak et al. also offer some relevant and recent conclusions (Nayak, Liu, and Tang 2015, 143155):

i. "*It is apparent that complex mixtures of phytochemicals rather than a single antioxidant in foods are responsible for health benefits because of their additive and/or synergistic effects. It would be biased to measure the antioxidant activity of fruits solely on the basis of the presence of vitamin C or any individual antioxidant compound in the raw or processed food*" (page 911);
ii. "*The role and contribution of water in the processed foods has not been investigated thoroughly for the measurement of antioxidant activity. Depending on the type of processing technique with different mediums of heating, the total antioxidant* activity could be underestimated in regards to the quantity of water present in the processed foods" (page 912);
iii. "*High temperature treatments can have detrimental effects on the phenolics and flavonoids, thereby reducing the antioxidant activities of processed fruits*" (page 912);

Table 8. Summary of the effects of technological treatments on the *in vitro* antioxidant capacity of fruit products.

Thermal	
Generic	• Short: ↓ by degradation of natural antioxidants and ↑ antioxidant compounds of the Maillard reaction • Long: ↓ then ↑ by production of antioxidant brown compounds of the Maillard reaction
Cooking & bleaching	• Bleaching: ↑ by increased extraction of polyphenols • Canned: ↑ by increased extraction of polyphenols
Drying, dehydration, freeze-drying …	• Air/sun drying: ↑ by water losses and ↓ by oxidation of antioxidant compounds • Freeze-drying: preserves antioxidant capacity better than conventional drying Vacuum microwaves > freeze-drying > air drying
Osmotic dehydration (confection/candied)	• ↓ by leaching soluble water compounds (e.g. phenolics) to the osmotic solution • The use of high concentrations of osmotic solution promotes greater retention of antioxidant capacity
Extrusion-cooking	• ? Lack of studies
Non thermal	
High pressures	• High pressure treatments on fruit products depend on food matrices and treatment parameters (pressure, time and temperature) and methods of analysis of antioxidant activity
Pulsed electric fields	• ↔ No marked effect but lack of studies • The intensity of the electric field, the pulse width, the pulse frequency, the polarity of the pulse, the processing time, or the shape of the pulse are among the most important parameters of high intensity pulsed electric fields affecting enzymatic inactivation, antioxidant activity and anthocyanin content: – Retention of antioxidant capacity increases as the width and frequency of the pulse increase – Bipolar treatments are much more useful than monopolar treatments in maintaining antioxidant activity
Radiations (ionizing or non-ionizing)	• ↑ by increasing the polyphenol content • Reduces phenolic losses during storage • The effect may depend on the intensity of the radiation • G-rays seem to be better at controlling antioxidant activity than ultraviolet
Ultrasounds	• ↓ by degradation of polyphenols (types anthocyanins): oxidation reaction promoted by interaction with free radicals formed during sonication + temperature rise
Supercritical CO_2	• ↑ by increasing soluble phenolic compounds and decreasing antioxidant losses during storage • Higher pressure results in higher inactivation of polyphenol oxidase • Prevents possible losses of other antioxidant compounds such as anthocyanins and b-carotene • Lack of information on the behavior of phytonutrients other than vitamin C and carotenoids, and polyphenols taken individually
Ozone	• ↑ by increasing phenolic and carotenoid compounds: ozone induces oxidative stress in the fresh product when it comes into contact with the plant tissue and induces various physiological responses, including the synthesis of antioxidants
Mecanical treatments (±thermal)	
Peeling	• ↓ by loss of antioxidant polyphenols in the skin
Juice pressing (±added sugars)	• Without added sugars: ↔ No marked effect • With added sugars: ↓ by dilution effect with added sugar
Nectar production	• ↓ by dilution effect with added sugar
Jam production	• ↓ by degradation of polyphenols and dilution with added sugar
Storage	• Stability then ↑ in long term: the formation of polymeric compounds during storage compensate for the loss of antioxidant capacity due to the degradation of the monomeric anthocyanins

iv. "*Degradation of higher molecular weight phenolics to lower phenolic compounds with potential antioxidative activity during various food processing operations could be compensating the overall antioxidant activity of processed foods*" (page 912);
v. "*Research focusing on optimization of thermal and non-thermal food processing operations has potential to retain phytochemicals in the processed foods*" (page 912).

In humans

If there are many intervention studies on the impact of the consumption of various fruits on the antioxidant capacity of the blood (or urine) in humans, very few have examined the influence of the transformation of the same fruit on this potential. In addition, there is no study on compotes and canned fruits.

However, the review by Serafini and Peluso may give a first general overview of the influence of different fruit-based products on antioxidant potentials in humans (Mauro Serafini and Peluso 2017). The authors went beyond fruit juices and synthesized intervention studies (n = 23) in humans regarding fruits, fruit juices, fermented fruits, freeze-dried fruits and extracts of fruits. Within the limits of the biomarkers used in these studies, no study reported an increase in oxidative stress in the subjects tested, regardless of their health status. Regarding fruit juices, seven out of eight studies show an improvement in the antioxidant status and one no effect; for fermented papaya, there is either no effect (two studies) or an improvement (two studies); for dried/freeze-dried fruit, there is either no effect (two studies) or an improvement (three studies); and for fruit extracts, four studies show no effect and three an improvement. Of all the forms of fruit tested, the juices seem particularly effective, also suggesting a higher bioavailability of antioxidant compounds from juices following extraction.

In an earlier meta-analysis based on 16 intervention studies, Tonin et al. reported that there was no significant difference between fruit juice and placebo for plasma total antioxidant capacity (TEAC assay), superoxide dismutase and catalase levels (Tonin et al. 2015). However, the juices were superior to controls in improving the blood level of vitamin C and in reducing the level of malondialdehyde. In addition, Lettieri-Barbato et al. showed, on the basis of a meta-analysis including eighty-eight intervention studies (both acute and chronic), that fresh and dried fruit (only in acute), red wine (both chronic and acute) and fruit juices (only in acute) significantly increased plasma nonenzymatic antioxidant capacity (NEAC) (Lettieri-Barbato et al. 2013). A review by Chang et al. discusses phytochemicals, antioxidant efficiencies and the potential health benefits of eight traditional dried fruits such as apples, apricots, dates, figs, peaches, pears, prunes and raisins and dried cranberries (Chang et al. 2016). On the basis of five intervention studies, the authors report an improvement in antioxidant status in humans with various dried fruits (Cao et al. 1998; Parker et al. 2007; Rankin et al. 2008; Valentová et al. 2007; Vinson et al. 2005).

The consumption of fruit products can also be accompanied by the consumption of dairy products. It is believed that the antioxidant properties of the dietary phenolic compounds of fruits are reduced *in vivo* because of their affinity for milk proteins (M. Serafini, Ghiselli, and Ferro-Luzzi 1996; Spencer et al. 1988). The study by Serafini et al. was conducted to provide some answers to this question (Serafini et al. 2009), and the researchers showed in healthy volunteers that the consumption of a fruit rich in antioxidants, such as blueberry, in combination with whole milk decreases its ability to increase plasma endogenous antioxidant defenses and to deliver bioactive molecules, such as caffeic acid, into the blood circulation.

Influence of processing on the fruit alkalinizing potential

All foods that are eaten give rise in the blood and in the extracellular fluid to acids and bases. The PRAL index measures the acidifying or alkalizing potential of foods in relation to the PRAL of this food (Remer and Manz 1995). It is in the urine that one obtains the measurement of this charge. This scientific measure therefore does not cover the entire phenomenon of acid-base balance in the human body. Although this index is often used in food dietetics, there is no scientific consensus on the consequences of its use for human health. The PRAL index therefore remains indicative of a potentiality. The formula for the PRAL index is as follows:

$$\mathrm{PRAL\ (mEq)} = [0.49 \times \mathrm{protein\,(g)}] + [0.037 \times \mathrm{phosphorus\,(mg)}] - [0.021 \times \mathrm{potassium\ (mg)}] - [0.026 \times \mathrm{magnesium\,(mg)}] - [0.013 \times \mathrm{calcium\,(mg)}]$$

Positive values indicate an acidifying potential, negative values indicate an alkalizing potential, and a zero result indicates neutrality. Acidifying foods or "acid producers" generate more acids than bases. These foods are mainly animal proteins (meat, fish, eggs, and dairy products). Their metabolism leads to strong acids such as hydrochloric acid, sulfuric acid, phosphoric acid or uric acid. However, cereals, especially when they are refined, also produce acids. Basifying or alkalizing foods generate more bases than acids. These foods are basically fruits and vegetables. Neutral foods (PRAL $\approx$ 0) have no influence on the acid-base balance. These foods are, for example, vegetable oils and refined sugars. It is advisable to maintain a good balance between acidifying and alkalizing foods, since an excess of acids can contribute to health problems with age.

Most fruit-based products are alkalizing, except for some complex processed dairy-based compositions (yogurt on a fruit bed, light fruit yogurt, brewed fruit yogurt, strawberry sundae) and desserts (apple pie), mainly based on citrus (*e.g.*, lemon sherbet and lemon custard), which are slightly acidifying (Table 9). Dried fruits are the most alkalizing, probably because of the loss of water that concentrates the compounds involved in the calculation of the PRAL. Of the fresh fruits, bananas are the most alkalizing and citrus fruits the least. Of the processed fruit, candied fruit is the most alkalizing, followed by fruit juice, fermented fruit (alcohol), canned fruits and fruit sirup. Complex fruit-based products are almost neutral, probably because of the higher levels of sugar and fat. The median value of the PRAL indexes for fruit products decreases with the degree of processing, from dried fruits to fruit desserts. This decrease is related to the PRAL formula, which suggests that the more fruit products are processed the less they are notably rich in potassium, magnesium and calcium, or even richer in phosphorus, with the protein content playing quite little because fruits contain only minor little amounts of protein.

Influence of processing on the fruit glycemic potential

The different fruits contain a highly varied mixture of glucose, fructose and sucrose, with each of these three simple sugars having its own glycemic index (Foster-Powell, Holt, and Brand-Miller 2002). Technological transformation, by releasing intrinsic sugars as extrinsic sugars and adding free sugars through the addition of sweeteners, can therefore modify the glycemic responses of fruits in humans. In this section, the influence of technological transformations on the glycemic indexes of fruit products will be analyzed according to two approaches: from officially published glycemic index tables and from original studies of the scientific literature.

From glycemic index tables

Table 10 presents the glycemic indexes obtained from studies in humans of fruit products according to their degree of transformation. All data are extracted from the glycemic index tables of Foster-Powell et al. published in 2002 (Foster-Powell et al. 2002). Note that no glycemic index data could be found for fruit compotes.

With few exceptions, overall fruit products have low (<55) to moderate (55–70) glycemic indexes. Processed fruits (with added sugars) have a slightly higher median glycemic index than minimally processed fruit products (approximately +9). Among the fresh fruits, there are large variations, with the extremes being cherry (glycemic index = 22) and watermelon (glycemic index = 72). Canned fruits are placed in the intermediate range (38 for canned peaches) and juices a little higher (50 for orange juice), but the data are less numerous. Concerning dried fruits, they tend to

Table 9. Alkalizing potential of fruit-based products according to their degree of processing (adapted from Piquet (Piquet 2012)).

Raw/dried fruits	PRAL index	Processed fruits	PRAL index	Complex fruit-based products	PRAL index
Dried banana	−27.5	Candied pineapple	−18.4	Bicuits with figs	−1.8
Dried apricot	−21.7	Candied fig	−10.5	Citrus beverage	−1.0
Raisins	−21.0	Candied pear	−10.1	Orange sorbet	−0.9
Dried fig	−18.1	Passion fruit juice	−5.7	Grenadine sirup	−0.6
Dried litchi	−16.3	Candied apricot	−5.0	Light yogurt on fruit bed	−0.4
Prunes	−13.4	Prunes in sirup	−4.0	Light sugar sorbet	−0.4
Dried date	−11.9	Rhubarbe compote	−3.8	Lemonade	−0.1
Raw plantain banana	−9.6	Canned apricot	−3.5	Orange soda	−0.1
Cooked plantain banana	−9.2	Mandarin juice	−3.4	Lemon lemonade	−0.1
Banana	−6.9	Candied cherries	−3.4	Natural yoghurt on fruit bed	0
Guava	−6.8	Grapefruit juice	−3.1	Lemon sorbet	+0.1
Black grapes	−6.1	Orange juice without added sugars	−2.9	Lightened fruit yoghurt	+0.1
Orange zest	−5.6	Orange and grapefruit juice	−2.9	Apple pie	+0.1
Kiwifruit	−5.6	Tropical fruit salad (canned)	−2.8	Sundae (strawberry)	+0.2
Papaya	−5.5	Cider	−2.5	Brewed fruit yogurt	+0.4
Cassis	−5.2	Grape juice	−2.5	Biscuit tray with fruit pulp	+1.0
Melon	−5.1	Lemon juice	−2.4	Lemon custard	+4.5
Fig	−4.9	Sweet cider	−2.4		
Grenade	−4.8	Red wine	−2.4		
Passion fruit	−4.6	Apple vinegar	−2.3		
White grape	−4.5	Sugar free apple juice	−2.2		
Apricot	−4.3	Plum with sirup	−2.2		
Currant	−4.2	Peach with sirup	−2.0		
Reine-Claude plum	−4.1	Sweet wine	−1.8		
Grapes	−3.9	Rosé wine	−1.8		
Guigne cherry	−3.8	Pear with sirup	−1.7		
Mirabelle	−3.8	Blackberry with sirup	−1.6		
Mango	−3.3	Canned cherries	−1.6		
Peach	−3.1	Fruits with sirup (canned)	−1.6		
Nectarine	−3.1	Wine vinegar, balsamic vinegar	−1.6		
Mandarin	−3.1	White wine	−1.5		
Orange	−3.0	Fruit salad (canned)	−1.4		
Cherry	−3.0	Apricot jam	−1.2		
Blackberry	−2.8	Light jam	−1.2		
Plum	−2.6	Dry white wine	−1.2		
Strawberry	−2.5	Fruit jelly	−1.1		
Raspberry	−2.4	Maraschino cherries	−1.0		
Litchi	−2.4	Orange marmelade	−1.0		
Pineapple	−2.3	Sparkling white wine	−1.0		
Lemon	−2.3	Sugar free fruit juice	−1.0		
Grapefruit	−2.3	Fruit paste	−0.9		
Asian pear	−2.2	Sweet dried cranberry	−0.8		
		Papaya nectar	−0.8		
		Peach nectar	−0.7		
		Pear nectar	−0.3		
Median value	−4.1	Median value	−2.0	Median value	−0.1

have highly variable glycemic indexes, from 31 for dried apricots to 103 for dried dates. There is no obvious explanation for these extreme values.

The effect of the degree of fruit processing on their glycemic index results from both the "composition" and "matrix" effects (Fardet and Rock 2018). Concerning the "composition" effect, remember that the fruits contain a mixture of glucose (glycemic index = 100), fructose (glycemic index = 19) and sucrose (glycemic index = 68). Thus, fructose is partly responsible for the low glycemic index of fruit products, which slightly distorts the interpretation of the indexes because fructose metabolization follows a different route than glucose, notably *via* the small intestine and liver (Jang et al. 2018). Thus, high levels of fructose (especially when added as fructose sirup resulting from the hydrolysis of cornstarch) in complex fruit products can lower the glycemic index, giving a "misleading" image of a positive health potential of the product while excess fructose is harmful to health (Ha et al. 2015). Concerning the loss of the "matrix" effect, the transformation of fresh fruits into juices, jams or marmalades (± added sugars) does not seem to have any marked effects on a potential increase in the glycemic index. Even if juice processing does increase the glycemic index, it is not very significant, except for grapefruit (whole fruit index = 25 and juice index = 48) and orange (whole fruit index = 42, unsweetened juice index = 50 and marmalade index = 48).

In 1998, Wills et al. studied the "composition" effect of fruits (n = 15) and vegetables (n = 9) to explain the variations in their glycemic indexes (Wills, Miller, and Matawie 1998). They found that the glycemic index of different fruits and vegetables varies from simple to triple, but no causal explanation of the differences has been advanced. This study examined the statistical relationship between published data on the glycemic index and nutrient levels in twenty-four fresh fruits and vegetables. The most significant relationships were a reduced glycemic index with an increase in organic acids, particularly malic acid, and the monosaccharides glucose and fructose, and an increase in the glycemic index with an increase in minerals. There was no significant correlation with sucrose, starch, citric acid, proteins, fats or vitamin C. The glycemic index is reduced by changes in

Table 10. Glycemic index of fruit-based products according to their degree of processing (adapted from Foster-Powell et al. (2002)).[a]

Raw, dried and unsweetened canned fruits and juices	GI	Processed fruits (with added sugars)	GI	Complex fruit-based products	IG[b]
Dried date	103	Lychee in canned and drained sirup	79	Roll-Ups®, processed fruit snack (Uncle Toby's, Australia)	99
Watermelon	72	Apricot in canned sirup	64	Strawberry processed fruit bars, Real Fruit Bars	90
Melon Cantaloupe	65	Peaches in canned sirup	58	Cookie Golden Fruit (Griffin's Foods)	77
Ripe banana	65	Apricot Spread	55	Fanta, orange	68
Raisins	64	Fruit cocktail with canned sirup (Delmonte)	55	Muffin with banana, oats and honey (Defiance Milling Co, Australia)	65
Dried fig	61	Cranberry Juice Cocktail (Ocean Spray)	52	Grany Rush Apricot (LU)	62
Black grapes	59	Strawberry jam	51	Banana, processed fruit fingers, Heinz Kidz	61
Pineapple	59	Orange marmelade	48	Apricot, coconut and honey muffin	60
Apricot	57			Blueberry Muffin	59
Papaya	56			Cocktail Lemon Squash	58
Kiwifruit	53			Nutrigrain forest fruits (Kellogg's)	57
Orange juice, unsweetened, reconstituted concentrate, Quelch brand	53			Fruity-Bix Bar, Dried Fruit and Nuts …	56
Banana	52			Alpen Muesli	55
Mango	51			Granny snack Apricot (LU)	55
Unsweetened orange juice	50			Fruity-Bix bar, wild berries …	51
Unsweetened grapefruit juice	48			Granny Snacks Fruits of the Woods (LU)	50
Unsweetened pineapple juice	46			Grain bar with apricots (puree)	50
Apple juice, pure, clear, unsweetened	44			Apple muffin	44
Unsweetened apple juice and cherry	43			All-Bran Fruit 'n Oats (Kellogg's	39
Canned pear (natural juice)	43			Raspberry smoothie	33
Peach	42			Soya/banana smoothie, 1% fat	30
Orange	42				
Sliced Apples, canned, solid packed without juice	42			Gran'Dia Banana, Oats and Honey (LU)	28
Unsweetened apple juice	40			Lightened sweet yogurt with acesulfame K and Splenda	24
Strawberry	40				
Plum	39				
Canned peach (natural juice)	38				
Pear	38				
Apple	38				
Dried apricot	31				
Dried apple	29				
Grapefruit	25				
Cherry	22				
Median value	46	Median value	55	Median value	56

[a]The glycemic index values are given with reference to a glucose test solution (glycemic index = 100).
bIncludes fruit products combined with dairy and/or cereal ingredients. GI, Glycaemic Index.

composition that increase the osmolality and nutrient concentration, thus delaying gastric emptying. It is also suggested that acidity *per se*, *i.e.*, pH, can have a direct effect on the glycemic index.

Previously, the glycemic index of apples, pears and kiwifruits was compared to their levels of total sugars and sugar compounds (Ha et al. 1992). Positive correlations between the glycemic index and total sugars and sugary compounds of kiwifruits were found ($r = 0.7$), but no such association was observed for apples and pears. The authors concluded that this suggests that some components of apples and pears inhibit the direct relationship between the sugar content of apples and pears and their glycemic index.

From original articles

Many studies have been dedicated to measuring glycemic responses following the consumption of different whole fruits, and many of these results have been included in the glycemic index tables of Foster-Powell et al. (2002). We will not review the data. However, studies measuring the impact of a technological process on the glycemic response of fruits are rare.

The "matrix" effect

In a pioneering study, Haber et al. showed in ten healthy subjects that the whole apple was less hyperglycemic and hyperinsulinemic than applesauce derived from these same fruits and that it was less so than an apple juice from these same fruits (Haber et al. 1977). This study thus highlighted the "matrix" effect of the fruits, where the state of destructuration (and thus of transformation) of the matrix increases from the whole apple to the juice, passing from a solid texture for the whole fruit, to viscous (or semisolid) for applesauce, and finally to liquid for the juice. It is also well known that a solid texture is more satiating than a semisolid texture and that a semisolid texture is more satiating than a liquid texture (Chambers 2016). These results were confirmed in 2017 in the study by Tey et al., who compared the effects of two fruit shapes (guava and papaya pieces and compote) on glycemic responses (Tey, Lee, and Henry 2017) in nineteen healthy adults and elderly subjects. All these fruit products had low glycemic indexes, below 50, but compotes gave significantly higher indexes (index = 42–47) than fruit pieces (index = 29–38).

The same type of result is also found in Bolton *et al.* in healthy volunteers where consumption of orange leads to a lower insulin response than orange juice and a lower post-absorptive glucose drop (Bolton, Heaton, and Burroughs 1981). However, with whole grapes, the insulin response was paradoxically higher than with grape juice. According to the authors, glucose in grapes is more insulinogenic than in apples and oranges. Conversely, grape juice leads to less pronounced insulinemia, probably because its high osmolality delays gastric emptying. However, diluting the juice does not increase its insulinogenicity. Additionally, the glycemic and insulinemic responses of the fruits seem to depend on both the fiber and glucose contents.

As noted in the study by Haber et al. (1977) technological treatments can modify the glycemic index of fruit products, especially following the destructuration of the food matrix. Thus, in the study by Jimenez et al., the glycemic index of the fruit of the peach palm (*Bactris gasipaes*), cooked (96 °C for 30 minutes) or in the form of chips, and of the fruit pulp of the dragon fruit (or *pitahaya*) were measured in 12 healthy adults (Jimenez, Gomez, Perez, and Blanco-Metzler 2012). The average value of the glycemic index is 48 for *pitahaya* pulp and 35 for cooked peach palm fruit, which can be classified as low glycemic index foods. The glycemic index of the chips is 60, corresponding to a food with a moderate glycemic index. Processing for the production of chips has therefore caused an increase in the value of the glycemic index compared to the cooked fruit, probably, according to the authors, because the grinding, molding and cooking stages favored the availability of starch during hydrolysis by digestive enzymes.

The peeling of fruits can also influence the glycemic index. Additionally, Katsilambros et al. studied the influence of pear and apple peel on the glycemic response (Katsilambros et al. 1985) in twenty-seven diabetic patients. No significant difference was observed in terms of mean blood glucose and serum insulin among the two meals (skinned or skinless fruit). Peeled and unpeeled fruit appear to produce the same hyperglycemia in type 2 diabetic subjects, despite the high fiber content of the skin.

Finally, Elizondo-Montemayor et al. studied the effects of HHP treatment of fresh mango puree on the glycemic indexes and postprandial glycemic responses of thirty-eight healthy Mexican subjects in a cross-randomized clinical trial; this type of new treatment is supposed to preserve the nutritional qualities of the mango, in particular the glycemic index (Elizondo-Montemayor et al. 2015). The average glycemic index for mango puree treated at HHP was significantly lower (index = 33) than untreated mangoes (index = 43). The viscosity and solubility values of HHP-processed mango puree samples were significantly higher, which influenced the glucose peak (T_{max}) at 45 minutes and induced lower AUC values by 20% compared to untreated mangoes. The results of this study support the interest in the use of HHP treatment to reduce the glycemic index of fruits.

Fruits with added sugars

The impact on the glycemic index of adding sugars to fruit juices is another issue of interest. Wilson et al. tested the impact of drinking unsweetened cranberry juice (low calorie, 19 cal/240 mL), and that sweetened with dextrose (normal calories, 120 cal/240 mL) compared to a control isocaloric drink (water with sugar, 19 and 120 cal/240 mL) on the glycemic and insulinemic responses in 12 subjects with type 2 diabetes (Wilson, Meyers et al. 2008). The main results showed that the addition of dextrose considerably increases the glycemic response of a fruit juice. In another study published the same year, Wilson et al. observed the same types of results with cranberry juice sweetened with high fructose corn sirup, *i.e.*, a higher glycemic concentration 30 minutes after consumption, although the differences are no longer significant after 180 minutes, as well as for the insulin response (Wilson, Singh, et al. 2008).

The last study concerns strawberry jam made with either sugar (sucrose), sugar and corn sirup, sugar and glucose, polydextrose (synthesized from dextrose and sorbitol), apple juice or maltitol (sweetener), consumed alone or with bread (Kurotobi et al. 2010). For jams without bread, the glycemic indexes calculated for thirty healthy subjects are 51 (sucrose), 74 (corn sirup), 70 (sugar + glucose), 47 (apple juice) and 17 (polydextrose). There was also a high correlation ($r = 0.969$, $p = 0.006$) between the actual glycemic index and the glycemic index calculated from the sugar composition of the jams. In the presence of bread, the differences are less clear.

Influence of processing on the fruit satiety potential

All fruit-based products

In 1995, Holt et al. measured, through a subjective assessment of satiety on a scale of 1–5, the satietogenic potential of 38 common foods divided into six food groups in 11–13 healthy subjects per group (Holt et al. 1995). They were able to define an index of satiety, with index 100 being the reference index of white bread. The groups "Protein-rich foods" (index of average satiety = 170 ± 13), "Carbohydrate-rich foods" (166 ± 24) and "Fruits" (170 ± 19) are on average the most satietogenic of the six groups, above Breakfast cereals with milk, Snacks and Confectionery, and various Bakery products. Whole fresh fruits therefore appear satietogenic, at equivalent levels with porridge or whole pasta. From these data, we developed the Fullness Factor (FF)™, which allows for a quick assessment of the satietogenic potential from the composition of the food (SELF Nutrition Data 2014):

$$FF^{™} = MAX(0.5, MIN(5.0, 41.7/CAL^{0.7} + 0.05\ X\,PR + 6.17E^{-4} X\ DF3 - 7.25E^{-6} X\ TF3 + 0.617))$$

where CAL is the calories per 100 g (30 minimum), PR is the grams of protein per 100 g (maximum 30), DF is the grams of dietary fiber per 100 g (12 maximum), and TF is the grams of fat per 100 g (50 maximum). The FF reasonably predicts the satiety responses given by Holt *et al.* for 38 foods (Holt et al. 1995). FF values range from 0 to 5. Foods

Table 11. Median satietogenic potential of fruits according to degree of processing (based on NOVA classification).[a]

NOVA Groups	FF
Group 1 (n = 68) : Un-/minimally-processed	3.37
Group 3 (n = 28) : Processed	2.99
Complex fruit-based foods (n = 28): processed/ultra-processed	1.64

aFF are calculated from from French Ciqual Data (ANSES-Afssa 2008). FF, Fullness Factor.

with a high FF are more likely to satisfy hunger with fewer calories. Low FF foods are less likely to satisfy hunger.

From the ANSES-Ciqual database, the FF of 124 fruit-based products could have been calculated according to the degree of processing (ANSES-Afssa 2008). The median results are presented in Table 11. Unsurprisingly, mainly because of a higher fiber content and secondarily due to a lower calorie content, the un-/minimally processed fruits have the highest indexes of satiety (median FF = 3.37), followed by processed fruits (FF = 2.96) and complex fruit-based foods (including various desserts) (FF = 1.87). In detail, carambola, rhubarb and fig are the most satietogenic (FF > 4.50) fruit products in the un-/minimally processed group; lemonade, fruit nectars and carbonated fruit beverages in the processed group; and sweetened fermented yogurt in the last group. As expected, the fruit-based products in the last group with the lowest FF generally have the highest densities of calories and lipids (*e.g.*, chocolate bar with dried fruit, fruit shortbread, strawberry pie, etc.).

Whole fruits versus compotes versus juices

Coming back to the pioneering study of Haber et al. on apple, compote and apple juice conducted with ten healthy adult subjects, the feeling of satiety 30 minutes postprandial was clearly the highest for the apple, followed by the compote, and then the apple juice (Haber et al. 1977). This difference between the three products lasted until an hour and thirty minutes after consumption and thus reveals the importance of the integrity of the food matrix on the feeling of satiety. In the same vein, Flood-Obbagy and Rolls tested in fifty-eight healthy adult subjects how the consumption of apples in different forms before lunch (apple, applesauce and apple juice with and without added fibers) influences the satiety and energy intake 15 minutes after lunch (Flood-Obbagy and Rolls 2009). The results showed that apple consumption significantly reduced dietary energy intake from lunch (preload + test meal) by 15% (187 kcal) compared to that in controls and reduced energy intake compared to applesauce and two apple juices. Satiety scores significantly differed after apples were consumed in different forms (apple > applesauce > both juices > control) (Flood-Obbagy and Rolls 2009), and adding natural levels of fiber to the juice did not improve satiety. According to a similar experimental design, Houchins et al. studied the effects of the shape of the food (solid fruit *versus* liquid, 400 kcal) consumed before a meal on the feeling of satiety that follows just after this meal in fifteen healthy adults and nineteen overweight or obese adults (Houchins et al. 2013). The solid fruits tested were apples, red grapes, and apples and raisins, while liquid foods were apple and grape juices. Appetite assessments were also obtained before and after eight weeks of increasing fruit and vegetable consumption (20% of estimated energy needs). The main results showed that "*Acute post-ingestive appetitive responses were weaker following consumption of fruits in beverage versus solid food forms*" and that "*consumption of beverage or solid fruit and vegetable food loads for 8 weeks did not chronically alter appetitive responses*". Mourao et al. also studied the influence of the shape of the food (watermelon *versus* watermelon juice, cheese *versus* milk, and pulp *versus* coconut water) on the daily energy intake in one hundred twenty obese and healthy adults (Mourao et al. 2007). The total daily energy intake was significantly higher, at 12, 19 and 15%, on days when the liquid forms of food were ingested, *i.e.*, watermelon, coconut and milk/cheese, respectively. According to the authors, these results showed that "*Food rheology exerts an independent effect on energy intake. Dietary compensation for beverages is weaker than for solid food forms of comparable nutrient content. Thus, they pose a greater risk for promoting positive energy balance*". These conclusions were also supported by an older study carried out in healthy volunteers consuming grapes or oranges (Bolton et al. 1981), where the feeling of satiety was greater after eating whole fruits than in the form of juice and the return of appetite was delayed (Bolton et al. 1981).

Finally, Moorhead et al. tested the level of carbonation (none, medium and high) of an orange juice drink (also containing added sucrose, citric and ascorbic acid) on satiety and food and short-term energy intake in thirty healthy subjects (Moorhead et al. 2008). Compared with the low carbonation beverage, the consumption of medium and high carbonation drinks ten minutes before consuming an *ad libitum* lunch led to a significantly higher satiety until lunch when dietary and energy intake were significantly lower. There were no significant effects on satiety after eating or food intake for the rest of the day.

Conclusions and perspectives

As a first conclusion, the scarcity of human studies that address the following issue has to be emphasized: "How does a change in fruits by processing modify the physiological parameters such as the antioxidant status, weight gain, and glycemic and lipemic responses?"

Is there a "process" effect for the fruit's health potential?

In most cases, a fruit product is the result of several treatments, often including both thermal and mechanical treatments – even fermenting in some cases – followed by storage. In addition, each of the treatments influences each of the individual fruit compounds differently. This double complexity of "compounds X treatments" makes it difficult to develop general laws on the influence of processes on the health potential of fruit treatment by treatment. However, if one again takes the simplified NOVA classification of un-/minimally processed, processed and ultra-processed fruits, one can begin to see some interesting and significant tendencies emerging (Table 12):

Un-/minimally processed fruits

Un-/minimally processed fruit-based products have a high nutritional density of bioactive compounds, but their digestive bio-accessibility remains limited because of the fibrous walls of the cells in which the compounds are "trapped". However, the scientific evidence that would prove that increased fruit nutrient bio-accessibility is desirable for health are lacking. The partial loss of this "matrix" effect with thermal, physical or mechanical treatments in added sugar-free compotes, purées and juices improves the bio-accessibility, and increases the glycemic index in parallel, which is less desirable. In addition, the antioxidant, alkalizing and satietogenic potentials of un-/minimally processed fruits are high, making them food products with high FHP.

Processed fruits

These are mainly fruit products with added sugars. The "matrix" effect is obviously altered because of the thermal and mechanical treatments, as with compotes, nectars and juice without added sugars, but it can still be well preserved in products such as "fruits in sirup" or "tinned fruits". The addition of sugars decreases and dilutes the nutritional density in protective bioactive compounds, tends to increase the glycemic index, and decreases the antioxidant, satietogenic and alkalinizing potentials.

Ultra-processed fruits

These products are mainly recombinant complex products incorporating fruit preparations and sodas and sirup/fruit juice-based drinks. Their nutritional properties have been significantly altered, including a loss of the "matrix" effect and a change to "red" of all nutritional indicators, except for the bio-accessibility, which can be increased for some bioactive compounds, but what are the health benefits if this only concerns a minor fraction of the initial bioactive compounds?

Which processes should be favored?

The analysis of the literature suggests that new nonthermal treatments such as HP or PEF could have advantages over more traditional treatments, such as thermal treatments in particular. There is indeed an increase in antioxidant potential, an increase in some phytonutrient levels and significantly lower losses of vitamin C.

The addition of sugar is quite common in fruit preparations, especially in compotes, juices, marmalades and jams. Sugar is not very satisfying and dilutes the nutrient density of fruits in phytonutrients, especially antioxidants. It can also increase the glycemic index (glucose) and promote insulin resistance (glucose and fructose) and reduce the alkalizing potential of fruits. Products without added sugar

Table 12. Synthesis of the effect of technological treatments on the health potential of fruits according to NOVA technological groups.

	« Matrix » effect	Nutritional density	Bio-accessibility	Glycemic index	Antioxidant potential	Satiety potential	Alkalizing potential
NOVA 1: Un/minimally-processed products: • Dried and fresh fruits • Cooking / bleaching, non-thermal treatments, pressing • Canned / compote / puree / juice without added sugar	↓ From fruit to compotes/puree then juices	High	Limited but ↑ with thermal (pasteurization, drying …), physical (high pressures …) and mechanical (grinding …) treatments	↑ From fruit to compotes/puree then juices ↓ With high pressures	High ↑ With fruit pressing	↓ From fruit to compotes/puree then juices	High
NOVA 3: Processed products: • Fruits in sirup • Canned / compotes / purees / juices / nectars with added sugar • Jams, marmalades and jellies	↓ From fruit to compotes/puree then juices	Medium	Medium The addition of milk ↑ bioaccessibility of lipophilic constituents but not that of hydrophilic	↑ From fruit to compote then with the juice, and with the addition of sugars	Medium : ↓ with added sugars and milk	↓ From fruit to compote then with the juice, and with the addition of sugars	Medium
NOVA 4: Ultra-processed product: • Fruits included in ultra-processed products (confectionery, cookies, ice cream, dairy products …) • Fruit drinks with aromas and additives (sodas …)	↓↓	Low	Very high	Very variable from one product to another	Low	Low ↑ with carbonation	Low

are therefore preferred, or at least replacing white refined sugar by nutrient-dense whole sugar.

Mechanical treatments (peeling, grinding, and pressing) tend to reduce the health potential of the fruits due to loss of the "matrix" effect (on the satiety), an increase in the bioavailability of the sugars, and losses of fiber and antioxidant polyphenols. However, they can also increase the digestive bio-accessibility of certain bioactive compounds by destructuring the fibrous walls, in particular that of carotenoids.

Are these effects true regardless of the types of fruit?

It is difficult to answer this question because the data are not sufficient, especially in view of the great diversity of existing fruits. In the scientific literature, berries and citrus have been well studied. Berries are particularly rich in anthocyanins and antioxidants, which makes it necessary to be vigilant about their transformation to preserve this important nutritional property as much as possible. However, since fruits tend to have common botanical properties – except perhaps banana, which are quite different – the rules regarding treatments seem to be quite applicable to all types of pulp fruit (pome or stone fruits).

"5 Fruits and vegetables a day"?

Although "5 fruits and vegetables a day" is a well-known nutritional recommendation, in view of the results reviewed here, it would be relevant to precisely state "preferably minimally processed". Fresh or dried fruits have the highest FHP in all respects: they are satietogenic, high in fiber and protective bioactive compounds, have moderate glycemic indexes, are rather alkalizing and are rich in antioxidants. Any treatment applied, involving storage, inevitably begins to diminish these potentials. The real issue is therefore to limit this decrease.

Intermediate fruit products such as, first, fruit purées and 100% fruit juice without added sugars, and, second, jams, fruits in sirup or canned fruits may be nutritionally interesting alternatives because they retain a part of their health potential, but it is altered by both a more or less important loss of the "matrix" effect and the loss or dilution of bioactive compounds.

Research gaps

This exhaustive review about the impacts of processing on fruit health potential has raised some research gaps. Notably, as regards with the crucial of food matrix on fruit health potential, more interventional studies are needed to study the "matrix" effect of fruit-based products, especially through interventional studies. In addition, results about the effect of processing on GI remains contradictory, notably due to the presence of fructose. Therefore, more studies are also needed to investigate - beyond the fructose content - how fruit matrix disintegration through processing may affect fruit-based product GI, *e.g.*, in whole fruits, fruit compote and purees and fruit juices. Finally, epidemiological studies take too little into account the processing effect on the risk of metabolic deregulation and chronic diseases associated with fruit-based products consumption.

Disclosure statement

Céline Richonnet is a registered pediatric dietician nutritionist and has been the Nutrition Director of the MOM Group since 2017. Anthony Fardet worked as a consultant for the MOM Group between July 2017 and May 2018.

Abbreviations

FF	Fullness Factor
FHP	Food Health Potential
GI	Glycemic Index
HHP	Hydrostatic High Pressure
PEF	Pulsed Electric Field
PRAL	Potential Renal Acid Load

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