PERSPECTIVE

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Current Food Classifications in Epidemiological Studies Do Not Enable Solid Nutritional Recommendations for Preventing Diet-Related Chronic Diseases: The Impact of Food Processing[1,2]

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ABSTRACT

To date, observational studies in nutrition have categorized foods into groups such as dairy, cereals, fruits, and vegetables. However, the strength of the association between food groups and chronic diseases is far from convincing. In most international expert surveys, risks are most commonly scored as probable, limited, or insufficient rather than convincing. In this position paper, we hypothesize that current food classifications based on botanical or animal origins can be improved to yield solid recommendations. We propose using a food classification that employs food processes to rank foods in epidemiological studies. Indeed, food health potential results from both nutrient density and food structure (i.e., the matrix effect), both of which can potentially be positively or negatively modified by processing. For example, cereal-based foods may be more or less refined, fractionated, and recombined with added salt, sugars, and fats, yielding a panoply of products with very different nutritional values. The same is true for other food groups. Finally, we propose that from a nutritional perspective, food processing will be an important issue to consider in the coming years, particularly in terms of strengthening the links between food and health and for proposing improved nutritional recommendations or actions. *Adv Nutr* 2015;6:629–38.

Keywords: food processing ranking, food groups, health potential, epidemiological studies, dietary guidelines

Introduction

National dietary recommendations are generally based on a systematic review of human-based studies that examine the associations between food groups and health outcomes; recommendations are also developed based on age and sex (1–3). Although terminologies differ between reports, the relations between food groups and disease prevalence are generally ranked as convincing, probable, possible or suggestive, or insufficient. However, obtaining definitive and convincing associations is very difficult because of the contradictory results for some food groups and associated pathologies (1–3). The origin of these apparent contradictions may result partly from the large diversity of products encountered in a specific food group. Indeed, foods with different processing types are mixed within food groups (e.g., fruit juices and whole fruits, whole-grain and sweetened breakfast cereals, and red and processed meat). In addition, many processed foods within a "food group" may have differential impacts on health. Consequently, by considering the processes applied to food, specific processed foods likely do not simultaneously increase and decrease the risk for a given chronic disease.

In addition, food health potential does not result from chemical composition alone but is also related to food structure, which involves nutrient interactions, starch structures (degree of complexation with lipids and of gelatinization or the amylase/amylopectin ratio), and matrix porosity and density (**Figure 1**) (4). Food structure characteristics are of prime importance because they can affect the feeling of satiety, nutrient bioavailability, and presence of fiber copassengers; all of

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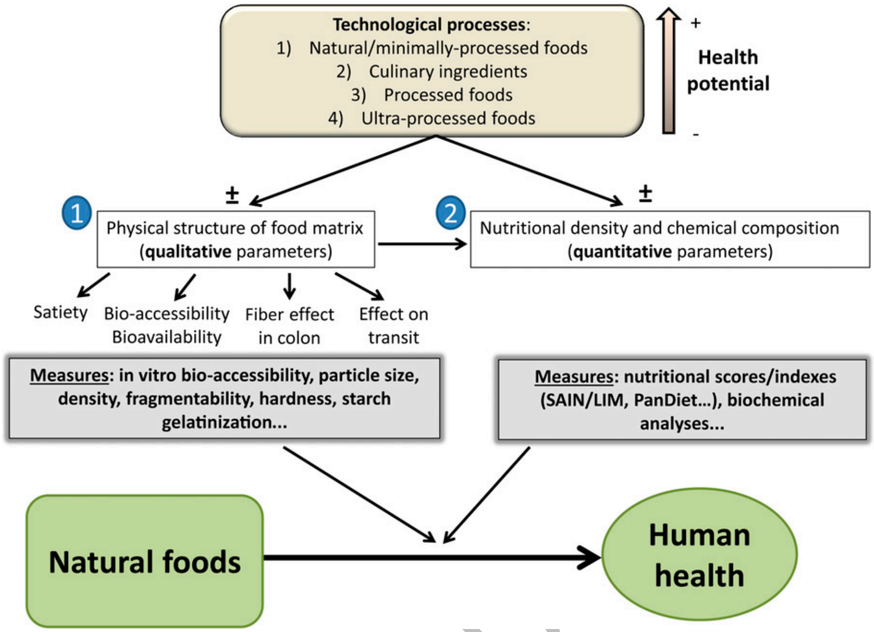

FIGURE 1 A new paradigm for the relation between processing, food health potential, and human health, with an emphasis on food transformation. We propose that food health potential should be first defined by both its food structure and nutrient density (4) and that the impact of processing on these factors should be more systematically and extensively measured. We then propose that processing conditions either decrease or improve food health potential (5). For SAIN/LIM, the SAIN score is a nutrient density calculated by the unweighted arithmetic mean of the percentage adequacy for the food positive nutrients, whereas the LIM score calculates the mean content of disqualifying nutrients in 100 g of food. LIM, a nutrient adequacy score for individual foods that represents the nutrient density per energy unit; PanDiet, probability of adequate nutrient intake that uses the national French and US dietary surveys; SAIN, a percentage of the excess of unwanted components (to limit) per mass unit.

these factors affect food nutritional value (Figure 1) (6, 7). However, the effect on food structure could be indirectly considered when foods are classified based on processing because the more food is processed the more its structure is generally fractionated and/or destroyed, such as with ultraprocessed foods (7).

Food classification based on the manner in which foods are processed seems to be more nutritionally relevant (8) compared with classifications based on the origin of plant and animal species. Researchers from the Center for Epidemiological Studies in Health and Nutrition at the University of São Paulo recently devised a conceptual framework in which foods are classified according to the nature, degree, and purpose of food processing. This classification grouped all foods into the following categories: *1*) unprocessed or minimally processed foods, *2*) processed food substances of culinary use, *3*) processed foods, and *4*) ultraprocessed products (see NOVA classification in **Table 1**) (8, 9). Current studies using NOVA have shown that industrial food processing is the primary force shaping the global food system; the most striking change in food supplies is the displacement of dietary patterns based on meals and dishes prepared from fresh and minimally processed food by those that are increasingly based on ultraprocessed food and drink products (10). Ultraprocessed products are industrial formulations manufactured from substances extracted from foods or synthesized from other organic sources that mostly contain little or no natural complex food. These products include sweet, fatty, or salty packaged snack products (e.g., ice cream, chocolate, candies, packaged breads, cookies, pastries, cakes, sweetened breakfast cereals, margarines, sauces and spreads, carbonated drinks, reconstituted juices), as well as most types of fast food (e.g., hot dogs, hamburgers, pizzas). Diets high in ultraprocessed products are energy dense, high in free sugars, unhealthy fats and salt, and low in dietary fiber (11, 12). These diets generally increase the risk of obesity and other diet-related noncommunicable diseases (13–15).

The emphasis on dietary patterns in recent epidemiological studies may help address this issue. Indeed, dietary patterns rather than food groups consider more realistic ways of eating by considering the ways differently processed foods are combined together into meals. Thus, recent observational studies and subsequent meta-analyses have tended to show that the prudent (16), healthy (16), vegetarian (17), Nordic (18), and Mediterranean-style (19) dietary patterns are more protective than the Western diet (20, 21). Whereas healthy dietary patterns are generally characterized by a high level of plant-based and/or local traditional foods (e.g., in the Nordic and Mediterranean-style diets), the Western diet is characterized by a high level of processed animal-based and/or refined foods, most of which are ultraprocessed food and drink products, i.e., formulated with previously refined ingredients (22). Although recent epidemiological studies with dietary patterns remain limited, initial results are consistent and more coherent because they consider the ways in which foods are combined and partly they are processed. For example, recent evidence from 3 cohorts in the United States demonstrated that the consumption of various ultraprocessed products such as cookies, white bread, sweets and desserts, sugar-sweetened drinks, processed meats, and French fries and chips was associated with weight gain in adults (23).

Our environment provides us with a large range of raw foods that are then transformed or processed (21). However, until recently, food processing has been underestimated in epidemiological research. Therefore, to gain a better insight

TABLE 1 The NOVA food classification[1]

Food groups and definition	Examples
Unprocessed and minimally processed foods: foods of plant (leaves, stems, roots, tubers, fruits, nuts, seeds) or animal origin (meat, other flesh, tissues and organs, eggs, milk) that are processed shortly after harvesting, gathering, slaughter, or husbanding; minimally processed foods are unprocessed foods altered in manners that do not add or introduce any substance but may involve subtracting parts of the food; minimal processes include cleaning, scrubbing, washing, winnowing, hulling, peeling, grinding, grating, squeezing, flaking, skinning, boning, carving, portioning, scaling, filleting, pressing, drying, skimming, pasteurization, sterilizing, chilling, refrigerating, freezing, sealing, bottling (as such), simple wrapping, and vacuum and gas packing; malting, which adds water, is a minimal process similar to fermenting that adds living organisms as long as it does not generate alcohol	Fresh, chilled, frozen, vacuum-packed vegetables and fruits; grains (cereals), including all types of rice; fresh, frozen, and dried beans and other legumes (pulses), roots, and tubers; fungi; dried fruits and freshly prepared or pasteurized nonreconstituted fruit juices; unsalted nuts and seeds; fresh, dried, chilled, and frozen meats, poultry, fish, and seafood; dried, fresh, pasteurized full-fat, low-fat, skimmed milk, and fermented milk such as plain yogurt; eggs; flour; "raw" pastas made from flour and water; teas, coffee, herbal infusions; tap, filtered, spring, mineral water
Processed culinary ingredients: substances extracted and purified by industry from constituents of foods or obtained from nature; preservatives, stabilizing, or "purifying" agents and other additives may be used	Plant oils, animal fats, starches, sugars and syrups, salt
Processed foods: manufactured by adding salt or sugar (or other substance of culinary use such as oil or vinegar) to whole foods to make them more durable and occasionally to also modify their palatability; derived directly from foods and recognizable as versions of the original foods generally produced to be consumed as part of meals or dishes; processes include canning and bottling, fermentation, and methods of preservation such as salting, salt-pickling, smoking, and curing	Canned or bottled vegetables and legumes (pulses) preserved in brine or pickled; peeled or sliced fruits preserved in syrup; tinned whole or pieces of fish preserved in oil; salted nuts or seeds; unreconstituted salted, cured, or smoked processed meats and fish, such as ham, bacon, and dried fish; cheeses made from milk, salt, and ferments; breads made from flour, water, salt, and ferments
Ultraprocessed products: formulated mostly or entirely from substances derived from foods or other organic sources; typically contain little or no whole foods; products are durable, convenient, packaged, branded, accessible, highly or ultrapalatable, and often habit-forming; typically not recognizable as versions of foods, although they may imitate the appearance, shape, and sensory qualities of foods; many ingredients are not available in retail outlets, whereas some are directly derived from foods such as oils, fats, starches, and sugar; others obtained by further processing of food constituents or synthetized from other organic sources; numerically, most ingredients are preservatives and other additives, such as stabilizers, emulsifiers, solvents, binders, bulkers, sweeteners, sensory enhancers, colors and flavors, and processing aids; bulk may come from added air or water; micronutrients may fortify the products; most are *designed to be consumed* by themselves or in combination as snacks or to replace freshly prepared dishes and meals based on unprocessed or minimally processed foods; processes include hydrogenation, hydrolysis, extruding, molding, reshaping, preprocessing by frying, and baking	Chips (crisps) and many other types of sweet, fatty, or salty packaged snack products; ice cream, chocolates, and candies (confectionery); French fries (chips), burgers, and hot dogs; poultry and fish nuggets or sticks (fingers); packaged breads, buns, cookies (biscuits); sweetened breakfast cereals; pastries, cakes, and cake mixes; energy bars; preserves (jams) and margarines; packaged desserts; canned, bottled, dehydrated, and packaged soups and noodles; sauces; meat and yeast extracts; carbonated and energy drinks; sugared and sweetened milk drinks; condensed milk; fruit yogurt; fruit and fruit nectar drinks; nonalcoholic wine and beer; preprepared meats, fish, vegetables, cheese, pizza, and pasta; infant formulas, follow-on milks, and other baby products; "weight-slimming" products such as powdered or fortified meal and dish substitutes

[1] Reproduced from reference 8 with permission. NOVA defines industrial food processing as "the methods and techniques used by food manufacturers and associated industries to make unprocessed or 'raw' foods less perishable, easier to prepare, consume or digest, or more palatable and enjoyable, or else to transform them into food products."

into the relation between processed foods and disease risks within epidemiological studies, it is important to have an objective classification of the different food products issued from the large diversity of technological processes. Without objective classification, products that have different nutritional qualities may be divided into a single group. This approach can lead to nonexplicative or nonsignificant associations with disease risk in epidemiological studies.

The new Brazilian dietary guidelines published in November 2014 are based on the NOVA food classification and national studies with dietary patterns of the Brazilian population (24). With this perspective in mind, we discuss the interest in using this paradigm of food classification based on processing (8) in epidemiological human studies and its implications for dietary recommendations. A classification according to food processing could be more nutritionally relevant, thereby providing a robust definition and criteria to discriminate transformed food to achieve better nutritional recommendations. Therefore, we hypothesized that a paradigm based on food classification that considers process type could result in more coherent results between observational studies. Thus, the first section will highlight the discrepancies in current scientific evidence that derives from studies that investigate only the associations between food groups without processing ranking and chronic disease risks, notably through examples of some international reports by expert panels. In the second section, the relation between the degree of processing and food health potential will be addressed based on some human studies. Finally, in the third section, the relevance of some objective technological indexes in association with food health potential will be discussed.

Association between Usual Food Groups and Chronic Disease Risk Based on International Reports

An analysis of recent and/or current national dietary guidelines between various countries may better illustrate the difficulty in achieving solid nutritional recommendations when scientific evidence is based on foods grouped by botanical origin and animal species.

The French National Health and Nutrition Program. Initiated in 2001 and extended in 2006, the French National Health and Nutrition Program has an overall goal of improving the health status of the general population by acting on nutrition as 1 of its major determinants. The last French National Health and Nutrition Program released in July 2011 recommended the following goals for individuals aged 18 to 74 y (25): *1*) fruits and vegetables at least 5 times a day; *2*) bread, cereals, legumes, and potatoes at each meal; *3*) milk and dairy products 2–3 times a day; and *4*) meat, poultry, fish, seafood, and eggs 1–2 times a day. These standards were followed by specific recommendations for added fats, refined sugars, beverages, and salt (25). The degree of processing was not directly specified or was at least not sufficiently emphasized, which is particularly problematic for cereals and dairy products, for which there is a wide range of very different products—from white rice to muesli and skimmed milk to cheese. Despite these national recommendations, the prevalence of obesity and type 2 diabetes has continued to increase in France. For example, 50% of adults were overweight or obese in 2014. Several reasons may have led to this phenomenon. The general population may agree with the nutritional recommendations but not adhere to them. In addition, the inconsistency in the recommendations and extensive advertising and supply of sweet, nutrient-poor, and fatty products may have increased obesity and overweight. We propose that a new processing-based food classification that strengthens the link between nutrition and health could better inform and protect consumers despite existing legislative constraints. However, changing such a paradigm is not easy. The proposal to affix colored markers according to the nutritional value of the food sold in France led to an outcry from the food industry and supermarkets. Indeed, these different colors directly implicated the technological processes and/or formulation applied rather than the food groups themselves. Thus, the same type of food (e.g., breakfast cereals) could have a product with a green (good nutritional quality) mark and another product with a red (low nutritional value) mark depending on the process applied.

Australian dietary guidelines. The last revised Australian dietary guidelines were published in November 2011 (1). Plant-based foods were globally ranked as fruits, vegetables, cereals, legumes, and nuts and seeds; animal-based foods as meat, dairy, fish, poultry and eggs; beverages as tea, coffee, sugar-sweetened beverages, and alcohol; and food ingredients as fats and oil, sodium and salt, and sugars. Dietary patterns were also included in these revised guidelines. This classification is common and currently used in most epidemiological studies investigating the associations between food groups and chronic diseases.

With these dietary guidelines, final statements are graded from A (high level of evidence) to D (low level of evidence), and study evidence is rated as excellent, good, satisfactory, or poor. However, when considering all combinations of food groups with disease prevalence, grade A has been obtained for only sodium and blood pressure. All other food groups have been assigned grades B, C, or D, with more grades C and D than grade B. Regarding the extensive amount of epidemiological data published to date, the absence of grade A usually reflects the limitations of the number of human-based studies (either interventional or observational), the lack of standardization, and the use of different adjustment parameters across studies. In addition, we suggest that studies can also fail to consider the degree of processing within food groups.

For example, dairy products are graded from B to D according to evidence obtained in different pathologies. Dairy products improve bone mineral density (grade C); are not associated with the risk of hip fracture, body mass index, weight change or obesity or breast, endometrial, and renal cancer (grade C); and are associated with a reduced risk of ischemic heart disease, myocardial infarction, stroke, hypertension, and colorectal cancer (grade B) and type 2 diabetes, metabolic syndrome, and rectal cancer (grade C), as well as an increased risk of prostate cancer (grade D). Accordingly, dairy products have been shown to affect organs and physiological functions differently. Moreover, regarding cancer risk, dairy products could be considered protective for rectal cancer and deleterious for prostate cancer. However, processing raw milk is known to lead to a large range of products with very different compositions and food structures. Each of these products is also known to result in different physiological outcomes and expected to have differential effects on biomarkers and the prevalence of chronic diseases, as recently shown for milk, butter, yogurt, and cheese

(26–29). Thus, the polemics regarding the health potential of dairy products continue to divide the general population. The same issue has begun to emerge with wheat-based products (30).

World Cancer Research Fund dietary guidelines: the second expert report. The World Cancer Research Fund/American Institute of Cancer Research 2007 report (an update of the first report published in 1997) offered 1 entry based on cancer sites and 1 on food groups (3). The report was based on systematic reviews and meta-analyses conducted by international centers from 7000 original scientific publications published up to 2006. An independent evaluation of the work was performed by a large panel of international experts based on a ranking of the validity of the studies as follows: prospective and interventional studies > case-control studies > animal studies. Relations between food groups and a given cancer site were then evaluated according to the level of evidence on a scale with 4 levels: convincing, probable, limited but suggestive, and limited with insufficient data to conclude. Only relations qualified as convincing and probable led to recommendations. Interestingly, in addition to the usual food groups defined in the previously described Australian report, this report also introduced 3 new groups: *1*) food production, processing, preservation, and preparation; *2*) dietary constituents and supplements; and *3*) dietary patterns. Concerning dietary patterns, this report included traditional and industrial patterns (Mediterranean-style, Asian, plant-based, and Western) and cultural patterns (vegetarian and vegan diets, religious, and healthy). Again, because of a lack of data, the panel could not draw any solid conclusions regarding the relation between dietary patterns and cancer risk (3).

Interestingly, the results based on different cancer sites were homogeneous for food groups with convincing and probable judgments, indicating that a given food group was not both protective and deleterious toward cancer risk. Food transformation included the methods of production (pesticides and herbicides, veterinary drugs, and genetic modification); preservation (drying, fermenting, canning, bottling, pasteurization, chemical preservation, and irradiation); processing (additives and packaging); and preparation (industrial cooking, steaming, boiling, stewing, baking, roasting, microwaving, frying, grilling, broiling, and barbecuing or charbroiling). Unfortunately, because of the lack of data, the authors concluded that there was not enough evidence to reach any conclusions regarding the association between production, preservation, preparation, and cancer risk, indicating that data regarding the influence of food processing (from production to preservation) on chronic disease risks are lacking. Indeed, most epidemiological studies to date have ranked foods within botanical and animal species groups.

A review of meta-analyses and systematic reviews. An exhaustive review of meta-analyses and systematic reviews from 1950 to 2013 for the association between food groups and chronic disease prevalence was recently published (31). Selected food groups and chronic diseases were similar to those included in the Australian report discussed previously. Difficulties in obtaining solid scientific evidence were discussed, and the conclusion was similar to previous reports and in agreement with most dietary guidelines (i.e., to favor the consumption of plant-based foods and decrease the consumption of red and/or processed meats, refined cereals, and sweetened beverages). However, the most solid evidence was obtained for ultraprocessed products (i.e., processed meats, sweetened beverages, and refined cereals). All studies demonstrated either a deleterious or absence of effects on disease risk for ultraprocessed foods and either a protective or absence of effects for other food groups that generally included less processed foods (31). This result agrees with the conclusions based on dietary patterns (22).

Some foods commonly considered to be healthy may become deleterious when submitted to a particular process, as illustrated by increased digestive cancer risks in some Asian populations (30) that consumed pickled vegetables in high amounts; indeed, salt-preserved foods may cause atrophic gastritis by directly damaging the gastric mucosa (32). In addition, although brown rice protects against type 2 diabetes, white rice increases its risk when consumed in high amounts (33). These examples tend to indicate that the process applied should be considered within food groups.

Ranking Food According to Processing: Practical Considerations

Considering food processing in epidemiological studies. Although few studies have been based on a systematic food-processing classification, the effect of processing on chronic disease risk has been tentatively investigated in several epidemiological studies. The processing classification is generally binary (i.e., comparing raw with processed foods), with no distinction for the intensity of processing; therefore, processed food products are generally poorly characterized. Indeed, food-frequency questionnaires in epidemiological studies have generally not been initially designed to consider extremely specific types of processing.

The most studied comparisons include raw with processed fruits and vegetables (34, 35), whole-grain with refined cereals (36–38), red with processed meats (39, 40), milk with yogurt with cheese (41, 42), and full-fat versus semiskimmed with low-fat/skimmed milk (or low-fat compared with high-fat dairy) (43, 44). For example, raw and processed fruit and vegetable products have been shown to protect against coronary heart disease risk, whereas only raw products protected against stroke (34, 35). Mixed results have been reported concerning whole-grain compared with refined cereals; whole grains have been shown to reduce the risk of hypertension (37) and visceral adipose tissue (38), whereas refined cereals have not been associated with hypertension (37) or breast cancer risk (36) and have been positively associated with visceral adipose tissue (38). Specifically, although brown rice has been inversely associated with the risk of type 2 diabetes, white rice has exhibited positive associations (33). Red and processed meats have been consistently positively associated with an increased risk of colon adenoma (39) and colorectal cancer (40). Results regarding dairy products have depended on the products and diseases considered with mixed effects; milk and yogurt have been shown to protect against cardiovascular risk, whereas no association was observed for cheese (41, 42). Moreover, no association was reported between cheese and whole-milk intake and prostate cancer risk, whereas skimmed/low-fat milk has been shown to slightly increase risk (43). Finally, yogurt and low-fat dairy seemed to protect against type 2 diabetes, whereas no association was observed for cheese and whole-fat dairy (44). Only a few examples have shown the importance of processing, but the heterogeneity of results still indicate the need for a more specific and systematic food classification system based on processing rather than a binary classification based on only raw compared with processed foods.

Influence of processing on lipotropic potential. A previous study evaluated the influence of food processing on the lipotropic potential (ability to reduce or prevent hepatic excess triglyceride deposits) of plant-based foods (45). Briefly, food processing was clustered into 3 main groups: *1*) thermal treatment (with or without water), *2*) refining, and *3*) fermentative processes (45). Processing significantly reduced the lipotropic capacity by ~20%, with fermentation being less drastic (change of −5%) than refining (−33%) and thermal treatments (−16%) (45). Based on the data drawn from the principal component and hierarchical clustering analyses, ultraprocessed plant-based foods (i.e., extremely refined products) tended to cluster together with similarly low or medium lipotropic densities. Catsup and chips had similar lipotropic profiles among refined products, whereas brewed tea and peeled cucumber had close profiles among minimally processed products (**Figure 2**) (45). Thus, 2 foods from distinct botanical origins were occasionally closer than 2 products from the same initial group.

Considering food processing in dietary guidelines. As outlined previously, Moubarac et al. released a study in 2014 that stated that their publication was the first to systematically review and assess the literature that methodically attempted to incorporate food processing into diet classification (8). Their reflection on food processing and health served as the basis for the release of the Brazilian dietary guidelines. The main point was that there was a link between the degree of processing, food nutritional quality, and health (11, 12, 46). According to Moubarac et al., a processing-based food classification system may help better understand "modern industrial food systems and supplies," "improve understanding of how to prevent and control overweight and obesity and diet-related conditions, including malnutrition as well as chronic non-communicable diseases," and "identify and promote essential and benign types of food processing and conversely to limit or eliminate unnecessary and malign types." Consequently, such a classification "will be a firmer basis for rational policies and effective actions designed to protect and improve public health at all levels from global to local" (8).

Despite these proposed strengths, the NOVA food classification (Table 1), which serves as the basis of the new national Brazilian dietary guidelines, should be tested in epidemiological studies in the near future by clustering populations into tertiles, quartiles, or quintiles of consumption for naturally/minimally processed, processed, and ultraprocessed foods and associating these clusters with diet-related chronic disease risks. However, food rankings according to process types will be difficult to incorporate in food-frequency questionnaires because these questionnaires have not been primarily intended for these types of classifications. Moreover, the NOVA classification does not address all of the consequences of food processing on nutritional quality and does not address home or culinary/cooking food processing. It is doubtful that any simple classification can address all of the consequences of food processing.

Proposition of Objective Indexes to Consider Food Processing within Food Groups

To better understand the advantages of a new food classification based on processing, we briefly summarized the basis of food processing to better understand its link with food health potential. The main issue was the intensity of processing or formulation, which shifted from common processed foods to ultraprocessed foods, with the latter generally associated with increased chronic disease risks.

A summary of basic process typology. Most food is subject to spoilage. With the exception of cereals, legumes, and oleaginous crops (i.e., grain products), foods are characterized by high water activity and nutrient content, which are ideal conditions for microorganism development. Transformation helps increase food shelf life from a few weeks to months or years while ensuring microbial stability, and different methods may extend it even more. The more common methods include thermal treatments (pasteurization and sterilization), composition changes (drying, salting, smoking, and candying), and modifying the microorganism ecology of the product (fermentation) (**Figure 3**). Shelf-life extensions, which commonly ensure safety quality, are often linked to nutritional quality depletion. Thus, greater shelf-life extensions are associated with poorer nutritional quality (47). However, the extent of degradation can be quite different as a function of the food/process combination (Figure 3) (48, 49). For example, stabilization can be achieved by thermal treatments. The resulting products have long shelf lives (>1 y) and high water activities. The nutritional quality may be impaired by reactions, especially at high temperatures (e.g., vitamin degradation). Microbiological activity may also be decreased by adding antimicrobial compounds (smoking) or decreasing water activity (drying, frying, salting, and candying). These processes lead to high dry matter and energy density. Finally, stability can be achieved by

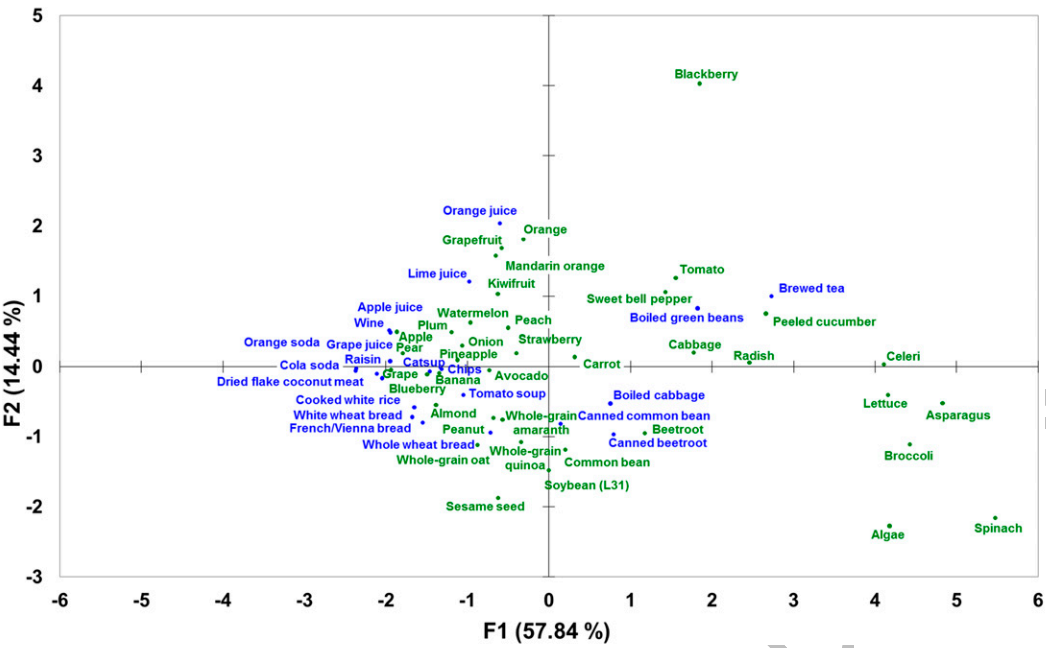

FIGURE 2 Principal component analysis score plots derived from a 59 (food items: 38 raw, 21 processed) × 8 (lipotrope densities/100 kcal) matrix (F1 × F2 plan represents 72% of total variance). The green and blue colors on the score plot correspond to raw and processed plant-based foods, respectively (F1 and F2 are principal components 1 and 2, respectively). PAI, potentially available myo-inositol (included myo-inositol moieties derived from soluble-free myo-inositol and glycosylated myo-inositol). Reproduced from reference 45 with permission.

microbiological composition changes. The resulting products have a medium shelf life but an interesting nutritional composition because the processes are nonthermal. The increase in probiotic and metabolites during fermentation may also increase the nutritional content of the food.

Processing versus nutritional impact. The simple process typology described previously may explain the different impacts of technological choices and why food diversity is important. Indeed, processes generally modify the initial nutritional quality in different ways based on objective and argued indicators. This research is not trivial because the process effects described in Figure 3 can differ as a function of the initial product and technological choices. For example, heat treatment can alter vitamins in fruits during canning. However, some antinutritional compounds (e.g., phytic acid in legumes) may also be degraded (50, 51). In addition, judging the nutritional impact of the processes must also include a nutrient bioaccessibility assessment. Indeed, even if the process degrades labile molecules, some molecules may become more bioaccessible to enzymes within the digestive tract after processing (7). This effect has been largely demonstrated for carotenoids in the vegetable matrix (52–54). Therefore, 2 different original raw products may be processed in the same manner, but their nutritional content, which is modified by the process in opposite ways, may be entirely different. Therefore, the intensity of processing in terms of unitary operation numbers is not always correlated with strong nutritional impact.

Defining objective processing- and nutritional-based indexes. An important research challenge is to better understand the diversity of processes from minimal to ultraprocessing. From a technological perspective, Figure 3 shows that a first categorization that includes product dry matter and shelf life could be used to discriminate between processed foods. Indeed, products that have a long shelf life and high dry matter are supposed to be energy dense, have low nutrient concentrations, and be produced by dehydration or formulation (55, 56). These foods are particularly convenient because they can be stored at ambient temperature without

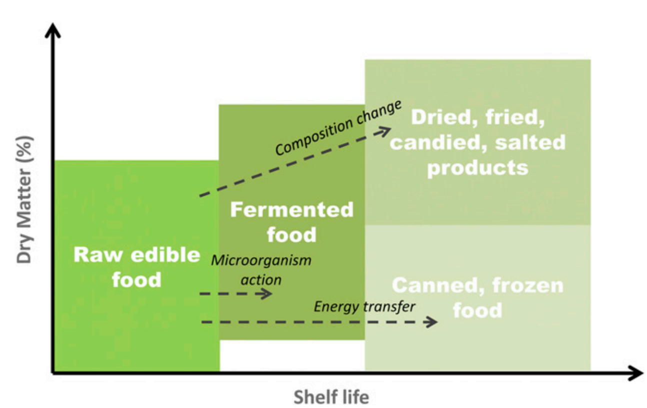

FIGURE 3 General principles of food stabilization. Shelf life is expressed as a function of dry matter percentage for the main food-processing methods (i.e., fermented, dried, and canned/frozen foods).

expensive packaging and are particularly palatable because of their high sugar, salt, and fat content (57). Such foods are cheap to produce and distribute (58, 59). Some formulations can be sophisticated and include previously processed ingredients (e.g., lactoserum, starches, and sugars) to increase dry matter and decrease water activity. Thus, these products have a high degree of refining/fractionation and recombination (i.e., ultraprocessed foods) (8). Finally, nutritional density, which may be correlated with the price of a product, should also be considered. Indeed, some products such as oleaginous seeds have high dry matter and a long shelf life but are not strongly processed or formulated. Moreover, they have high unsaturated fatty acid or vitamin content (60).

In addition to technological indexes, nutritional profiling systems could also help classify processed food and discriminate between nutrient-dense and -poor products (58, 61). For example, a previous study demonstrated the interest in using a nutritional profiling system to evaluate the processes used for different fruits and meat products; the nutritional SAIN-LIM scores were calculated during processing and very distinctly discriminated between different technologies, including formulation (candying and salting), and other processes (55). However, such indexes are less useful for ultraprocessed products because they do not truly consider the effect of processing on food structure (e.g., fractionation–recombination processes).

Conclusions and Perspectives

To date, most epidemiological studies have clustered foods into groups of the same botanical or animal species origin. Because diet-related chronic disease risks are associated with a high consumption of ultraprocessed products, we propose that current research should focus on considering a food classification that includes food processing that can be applied to data collection within the framework of epidemiological studies (4). Food consumption assessed from food-frequency questionnaires should not be derived from botanical and animal food groups but according to the different degrees of food processing. The NOVA food classification may serve as a basis for this purpose (8). Notably, such a typology could be of great interest in developed countries, where the consumption of highly transformed industrial food continues to increase. However, a first step could be considering food processing within food groups, a transitional solution before adhering completely to food ranking according to processing only.

The impact of processing on food structure should also be considered when measuring the impact of processing on food nutritional potential. However, this issue is more complex to measure because adequate technological indexes to measure the impact on food structure are lacking. Indeed, a table of food structure parameters according to the processes applied does not currently exist. Therefore, a large amount of data collection concerning the effect of processing on both food structure and nutritional composition is needed.

Finally, from a nutritional perspective, we propose that food processing will be the key issue to consider in the coming years, particularly when proposing improved nutritional recommendations based on the process applied to each food group (5, 8–10). Furthermore, research must consider the ways in which food is combined through culinary preparations and the ways food is eaten (i.e., the context of eating), which influence consumption patterns and have important health implications (8).

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