npj | science of food

Article

Published in partnership with Beijing Technology and Business University & International Union of Food Science and Technology

https://doi.org/10.1038/s41538-025-00395-x

Defining the role of processing in food classification systems—the IUFoST formulation & processing approach

Lilia Ahrné[1], Hongda Chen[2], Christiani J. Henry[3], Hyun-Sook Kim[4], Barbara Schneeman[5] & Erich J. Windhab[6] ✉

The Task Force on Food Processing for Nutrition, Diet and Health established by the International Union of Food Science and Technology (IUFoST) has developed a rational approach to determine the impact of food processing on the nutritional value of processed foods, called the IUFoST Formulation and Processing Classification (IF&PC) scheme which is comprehensively reported here. The purpose of developing this scheme is (A) to address the current confusion between formulation and processing and thereby offer assistance to improve and refine the controversial NOVA classification system, and (B) to explore the potential for considering other relevant essential food attributes, such as (a) safety, (b) sustainability, (c) palatability, (d) affordability, and (e) convenience in food product classification. The authors recommend that this IUFoST initiative be further investigated and complemented based on concerted R&D interactions of food scientists, food engineers, and nutritionists.

IUFoST established an international task force on Food Processing for Nutrition, Diet and Health to discuss and propose a rational approach to define the impact of food processing on the nutritional value and health implications of processed food products. The goal is to develop recommendations offering assistance in refining and improving the NOVA classification system to address ambiguities and uncertainties in the classification approach that have caused criticism and confusion about applying NOVA. The NOVA concept of Ultra-Processed Food (UPF) has expanded globally. It is used by the general public although the definition or meaning of the phrase as used is not always clear, nor are the criteria for identification of foods included in the "ultra-processed" category explicitly or quantitatively defined. The task force critically analysed the NOVA classification system and used it as a template to suggest improvements based on scientific rigour and analysis.

The processing of food can have both positive and negative influences on product properties including product safety and nutritive quality. Clearly, these critical issues require quantitative assessment and practical, evidence-based definitions. The task force determined that formulation (F) and processing (P) must be expressed as separate influencing factors on the food property in focus to achieve these goals. As such, the nutritional value was exemplarily chosen, which represents a significant influencing factor to obesity, an array of non-communicable diseases, and associated health risks addressed by the NOVA classification system. Respective parameters must be developed to describe levels of formulation and processing quantitatively. Consequently, the task force defined formulation as "Systematic selection of relative quantities of ingredients for a food product" and processing as "Treatment of a food material to achieve a desired effect" so that it could examine approaches to quantify each parameter and its impact on the overall nutritional value (NV). The task force determined that formulation aspects can be derived from quantitative estimates of the content of nutrients and nutrient-related components in a food, whereas processing aspects should be derived from the change in this content that occurs due to processing. To provide examples of how such a system could work, the task force chose the Nutrition Rich Food Index (NRF[1]) as the base for (i) defining the nutritional value by quantitative description of the content of nutrients and nutrient-related food components that are derived from the food's formulation and for (ii) suggested extensions to consider a wider range of nutrients, nutrient properties and consumer groups. For quantification of the processing impact on the nutritional value, the difference in the NRF (ΔNRF) between the food product before and after a processing treatment is determined. The resulting quantitative two-parameter classification regarding formulation (F) and processing (P) can also be described using the

[1]Department of Food Science, University of Copenhagen, Copenhagen, Denmark. [2]National Institute of Food and Agriculture (NIFA), USDA, Washington, DC, USA. [3]Singapore Institute of Food Biotechnology Innovation (SIFBI, Singapore, Singapore. [4]Department of Food and Nutrition, Sookmyung Women's University, Seoul, Korea. [5]Food Science and Nutrition, UC Davis, Davis, CA, USA. [6]Institute of Food, Nutrition and Health, Swiss Federal Institute of Technology Zürich (ETH), Zürich, Switzerland. ✉e-mail: erich.windhab@hest.ethz.ch

introduced nutritional value-related Formulation and Processing Food Index $FPFI^N$. This links and weights the F&P influences to illustrate their interaction with the nutritional value of a processed food in an integrally simplified manner. A colour scheme supports the representation. The value of this approach, denoted as IUFoST Formulation & Processing Classification (IF&PC) scheme is to offer assistance in refining and improving the NOVA classification base by addressing the confusion between formulation and processing and the non-quantitative assessment in the NOVA system. Eliminating these weaknesses could provide the basis for a significantly improved understanding of the nutritional value of processed foods at the point of purchase and the relationship of this parameter to obesity and other diet-related diseases which is a stated intention of the NOVA classification approach. Since nutritional epidemiology aspects were not treated in further detail, focus was on nutrient density of individual foods and their related contribution to the quality of the diet.

A contribution of the NOVA approach has been to initiate discussion of processing as an important impact factor besides formulation on consumer-relevant food classification. The proposed IF&PC modifications are the next step needed to accurately consider processing as a factor in assessing the nutritional value of foods. Defining formulation and processing explicitly and quantitatively, as illustrated in this work, does not directly address other concerns raised by the NOVA classification system, such as the sensory aspects of foods, which are likely to be subjective. However, such a definition and its use to develop a Nutritional Value score of food products that includes both formulation and processing will enable the design of research studies to evaluate subjective responses to foods that vary in formulation and/or processing. Moreover, the presented IF&PC approach has the potential to enable consideration of further food property characteristics, thus supporting a more practical yet even diverse food classification approach.

Based on the analysis of steps needed to consider processing in systems that evaluate nutritional quality, the IUFoST task force calls on food and nutrition scientists to carry out joint research and development work to validate and expand the proposed IF&PC classification concept for differentiated, quantitative consideration of formulation and processing. Such research is essential to improve the ability to determine the correlation between nutritional product quality, related to both formulation and processing and possible effects on health-related aspects, as well as to design more suitable clinical trials to validate such associations and contribute to our understanding of what changes are needed in our food system.

It is widely recognized that dietary habits can affect the aetiology of chronic diseases. The development of dietary guidelines has been advocated to improve health and well-being of populations. Dietary recommendations are promulgated to help consumers with food choices. Furthermore, several nutrient density (ND) and nutrient profile (NP) models have been developed to assist food classification for dietary guidelines[2–4]. Many nutrients or combinations of nutrients, such as sodium and sugars in the diet, have been identified as common risk factors for noncommunicable chronic diseases (NCCD). In many markets, nutrient information is provided on food packaging, and regulations govern food labelling and uses of health claims on food packaging. Food-based dietary guidelines (FBDG) published by authorities in different countries emphasize dietary patterns that provide adequate nutrition while limiting the intake of nutrients and food components associated with the risk of NCCDs. A technical manual was developed by FAO and WHO for the preparation and use of FBDGs, which recognized that such guidelines must consider local factors that affect food availability and intake as well as nutritional status (https://www.fao.org/nutrition/education/food-based-dietary-guidelines). In some markets, food packages provide information in colours, number of stars, or traffic lights-type illustrations on energy, fat, and salt contents of various packaged foods. Particular examples of the inclusion of nutritional information by using a scoring system and ratings on packaged foods to consumers are the NutriScore (several EU countries) and Health Star (Australia, New Zealand) ratings. In a comparison between different nutrition profiling systems the Nutrient Rich Food Index (NRF) has shown advantages in (i) comprehensive nutrient consideration, (ii) strong scientific basis, (iii) flexibility for different applications, (iv) capturing the overall nutritional value, (v) adaptability for different populations and (vi) detailed nutrient density assessment for nutritional scoring of foods (e.g. ref. 5). The NRF was developed to account for nutrients to include and avoid in diets, and it has been widely promoted and validated[4,5]. The aim has been to provide a measure of nutrient composition in relation to the energy content of foods. The development of these profiling systems relies on nutrition requirements and guidelines that are based on the best scientific evidence on food and health that relates to food intake, food composition, and public health risks. For example, energy from foods is essential; however, excess energy intake contributes to obesity and foods that provide energy with little or no nutrient content may compromise the ability to meet nutrient needs and maintain energy balance. Compositional data on foods have been made available in databases, and nutritional information is also available on food packaging. Compositional data for fabricated foods may be calculated from the composition of ingredients or by using compositional analyses as directed by regulations of particular market areas. In other words, food formulation quite often determines food composition and thereby its nutrient content before consumption of the food.

The development of a fundamentally different approach to relating public health risks and food intake was initiated by Monteiro et al.[6]. They proposed that the level of food processing contributes to obesity and other dietary diseases and as such presents a public health risk[7]. Monteiro et al.[8] divided foods into four categories and introduced a food classification known as the NOVA classification. The NOVA food categories are: (1) unprocessed or minimally processed foods, (2) processed culinary ingredients, (3) processed foods and (4) ultra-processed foods (UPFs). The introduction of the NOVA classification has promoted the use of food technological terminology, particularly food processing and variations of the word processing to describe the health risks of foods from the different NOVA food categories. The concept of UPF has globally expanded to general public use, although there is neither any clear definition for the meaning of the phrase nor for identification of foods included in the ultra-processed category. Furthermore, the expectation that an assignable level of processing underlies the distinction between non- or minimally processed, processed, and ultra-processed is not met. As qualitative processing descriptors, the NOVA system implies the extent of change, nature of change, place of processing, and purpose of processing[9]. Any quantification of such is missing. Instead, formulation aspects like the addition of sugar, salt, saturated fats and "cosmetic" ingredients (additives, synthetic micronutrients) are described as a major criterion to transfer foods from minimally processed or processed states to ultra-processed one. Such vague definitions and ambiguities have led to critical discussions on the NOVA system. In the meantime, the NOVA classification has already been introduced in South America. The frequently heard argument that NOVA represents a simple classification system is offset by the difficulty of its application due to described ambiguities and unquantified assessment criteria. The following two questions, therefore, arise: (A) does the influence of processing on the nutritional properties of foods represent an important factor in their evaluation for dietary guidelines to be considered in a quantifiable way, and (B) Can the NOVA classification system provide an alternative or even improved basis for the creation of dietary guidelines. The recent literature on the purported negative impact on health ascribed to the consumption of UPF using the NOVA classification is largely based on epidemiological studies. Since such studies represent an association rather than causality, we believe that our present report can provide more clarity on what is precisely meant by processing and whether or how it could be used to improve processed food product classification.

IUFoST established the International Task Force on Food Processing for Nutrition, Diet and Health (FPNDH) to address the impact of processing on food quality characteristics and explore measures for quantification of processing impact on such in the context of processed food products' classification. It is well known that processing enables the creation or modification of food structures on different length scales, from molecular to

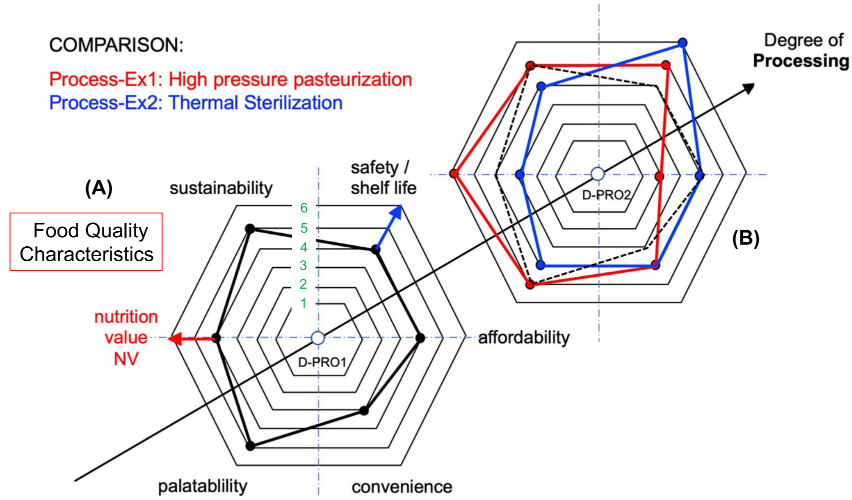

Fig. 1 | Hexagonal spiderweb diagram with inserted food properties and their normalized grades. A Hypothetical product quality characteristics profile indicated by a black line within the hexagonal spiderweb diagram. Properties to be optimized are indicated by red (nutrition value) or blue (safety/shelf life) arrows. **B** Hexagonal spiderweb diagram with product property profiles for differently processed base product (Red: High-pressure pasteurization for optimized nutrition value but compromise for safety/shelf life; Blue: Thermal sterilization for optimized shelf life but compromised nutrition value).

macroscopic. These changes in turn determine related product properties such as safety, nutrition value and digestibility, palatability, convenience, affordability and systemic characteristics like sustainability and possible public health impact aspects. Hence the IUFoST task force supports consideration of processing impact in food classification as basically suggested by the NOVA classification system but with the intention to suggest and examine a quantitative approach for refinement and improvement of such implementation in order to provide clarity and certainty.

As a final introductory remark, it is important to remember that nearly a billion people do not meet their nutritional needs in the world today. Many live in the developing world. The provision of nutrient-dense foods in such populations is only possible by the inclusion of processed foods. This highlights the need to clearly define the concept of processing and formulation, as the NOVA system has introduced ambiguities that have led to confusion among many who have attempted to apply it or even caused rejection of the inclusion of processed foods in meeting the nutritional needs of a healthy population.

Results and discussion

Background and objectives

The concept of UPFs has created controversies and, therefore, the use of food processing terminology in food classification should be comprehensively reviewed. IUFoST also recognized an international need for food classification underpinning dietary guidelines and policies as well as public health-related decisions that are based on scientific evidence and data to support objective decisions across the involved sectors and that consider global diversity in nutrition issues and food choices. Developing a research agenda for understanding the role of processed foods in the FBDG requires that food processing concepts be clearly defined and understood by scientists conducting such research across several disciplinary areas.

Thus, it was decided that the IUFoST task force on Processing for Nutrition, Diet and Health (P4NDH) will prominently address the question of how quantitative consideration of processing as an impact factor on specific quality characteristics or the overall quality profile of processed food products could be introduced.

Key definition 1: Classification of food properties

Food classification involves systematically arranging foods in groups or categories according to established criteria. The latter should be food quality criteria in the present case. Such are (i) safety, (ii) palatability, (iii) affordability (iv) nutrition value, (v) convenience and (vi) sustainability. The latter relates to the environment, health, economics and society.

As demonstrated in Fig. 1, the properties (i) to (vi) can be used to configure a property profile of a food product which is typically shifted by processing. In case optimization of one of these properties is intended some others may be compromised. A property profile for an exemplary base food product is shown in Fig. 1 (part A), which is indicated by a black line before processing treatment. After hypothetical treatments by two different processes (e.g. Process P1: high-pressure pasteurization (red line) and Process P2: thermal sterilization (blue line)) carried out to optimize either the nutrition value by more gentle treatment of heat-sensitive nutrients (P1) or the product shelf live reducing the microbial load by more intensive thermal decontamination treatment (P2), the respective changes in the property-profiles are shown in the hexagonal spiderweb arrangement in Fig. 1 (part B). This represents a typical balancing procedure of food product properties in an industrial environment if optimization of one or some of the properties shall be achieved. The processing toolbox is typically very flexible through the adjustment of processing type and parameters.

The NOVA classification system emphasizes the impact of ultra-processed foods with a focus on the nutritional quality of overall diets, and associated obesity and health/disease outcomes[7]. Palatability is mentioned in some places as a reason for overeating. Accordingly, the task force identified nutrition value (NV) and palatability as key target properties to be addressed in this context. For the first exemplary approach followed in this report, the nutrition value was the priority, due to its expected improved quantitative definability based on objective criteria. In contrast, considering palatability will require additional subjective criteria to meet a wider spectrum of consumer preferences.

Furthermore, the Nutrition Value (NV) constitutes the base for the derivation of dietary guidelines which, if applicable, should be taken into account for the implementation of processing criteria to be quantified. The NOVA system considers the addition of sugar, salt and saturated fats as indicators for food products classified as processed and ultra-processed. For the latter nutrients/components extracted from foods to imitate or enhance the sensory qualities of foods ("cosmetic ingredients") come on top[7].

The object of classification (OC) in the thematic context of the IUFoST task force work was the processed food product at the Point of Purchase (POP). In general classification sorts into classes of quantified Classification Parameters (CPs) which are functionally related to a selected PROPerty (PROP) of the targeted object. For a better understanding of classification definition and related designations, this is schematically demonstrated in Fig. 2.

To characterize a food product in its state at the POP, the parameters related to the PROP to be considered for classification (CPs) are determined preferably by quantitative measurement but may also be qualitatively described.

As the Point Of Classification (POC) in principle, each position along the food value chain can be selected for a food product in its local state. The definition of the Food Value Chain in the context of this report does not end on the consumer's plate but includes the digestive and metabolic

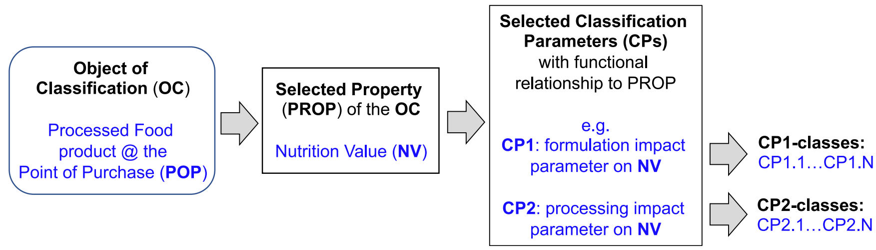

Fig. 2 | Classification and related designations. Food Product at the Point of Purchase (POP) as the Object of Classification (OC) of which the Nutrition Value (NV) is considered as the selected Property (PROP). Related Classification Parameters (CPs) chosen here are: Formulation impact on NV (as CP1) and Processing impact on NV (as CP2). For both, CP1 and CP2 classes CP1.1 to CP1.N and CP2.1 to CP2.N describing related quantitative degree ranges of impacts are distinguished.

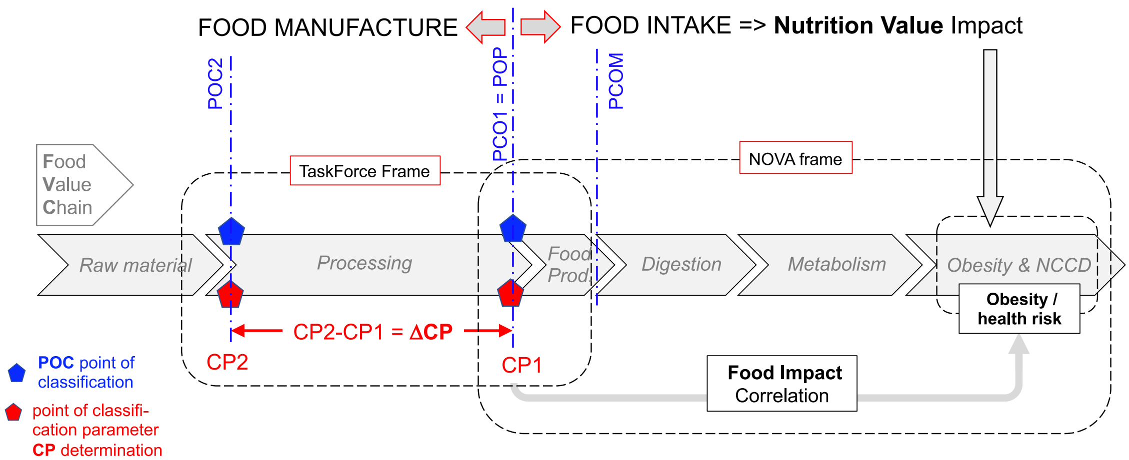

Fig. 3 | Schematic demonstration of choice of Points of Classification (POCs). Points of Classification (POCs) for determining the processing impact on the classification parameters (CPs) and frames of intended classification applications for the suggested IUFoST task force approach and the NOVA system. Within the NOVA frame digestion and metabolism are not addressed, but only a qualitative, non-evidence-based correlation (here denoted as food impact correlation) is associated between the classified nutrition value at the Point of Purchase (POP) and obesity/health risk aspects resulting at the end of the extended food value chain.

transformation steps of the consumed food as well as the resulting consumer's status with respect to obesity risk and other health risk outcomes. The task force decided to refer to the food product at the point of purchase (POP). Home preparation may occur between the POP and the Point of Consumption (PCON), including processing steps. However, since both the conventional nutrient recommendation schemes used for dietary guidelines and the NOVA classification refer to processed food products at the POP, home processing being astonishingly exempt from the NOVA definition of ultra-processed food, is also not considered here in further detail but is understood to potentially further modify a food's nutritional value depending on how the food is prepared which may not strongly differ from industrial processing steps but being in general less controlled.

An important boundary condition for proper classification is that the classification parameters (CPs) are determined at the POC (here POP). Other key specifications made by the task force for the introduction of classification parameters (CPs) for processing were:

(i) A second POC2 can be selected upstream of the food value chain from the POC1 (=POP), to describe a CP value change as the result of a processing sequence between these two points (ΔCP-values).
(ii) In such case (i) the definition of the CP has to be the same at each of the two POCs (CP1 @ POC1 = CP2 @ POC2).
(iii) If (ii) is not fulfilled, only correlations between classification results achieved at POC1 and POC2 are applicable.
(iv) An exception to (iii) is given in case a functional relationship between CP1 @ POC1 and CP2 @ POC2 has been identified.
(v) In case a second POC2 is selected downstream the food value chain from PCON, it has to be expected that the probability of point (iii) to occur is high as long as functional relationships between CPs at different POCs along the digestive and metabolic processing tracks are not quantitatively known.

Figure 3 demonstrates the "POC cases" addressed in (i)–(v) before. It also includes indications of the different application frames for the suggested classifications by the IUFoST task force and the NOVA system.

As mentioned in (i) and demonstrated in Fig. 3, ΔCP-values are a measure of the treatment (processing) influence on the food product between two POCs. Accordingly, the ΔCP-values can serve as classifying parameters for the food processing impact experienced before the POP, hence describing the losses or gains of the nutrition value between the unprocessed or pre-processed state and the POP. In case the processing track before the POP consists of a series of n processing steps each of these steps could be analysed by respective ΔCP_1 to ΔCP_{n-1} values. The Nova frame of classification as it is interpreted nowadays spans from the POP as a point of classification (POC) to the end of the extended food value chain where obesity and NCCD health risks are claimed to be considered. The NOVA classification at the POP considers four qualitatively described NOVA classes. These classification results are compared with results from observational studies on resulting obesity and health risk aspects. Such comparison is of a correlation nature since quantitative functional relationships between food product and nutrition value parameters along the digestive and metabolic tracks are so far only fragmentary available but not addressed by NOVA. Thus, it is suggested to designate such derived relationships between food product parameters at the POP and obesity and health risk data as "Food Impact Correlations" (Fig. 3).

Key definition 2: Food processing

To focus on Food Product classification with respect to the Nutrition Value as targeted property and taking the possible impact of processing on such classification into account, the process-property relationship designated the main element of interplay to be addressed. As has been shown in the food engineering literature, a quantitative understanding of how processing

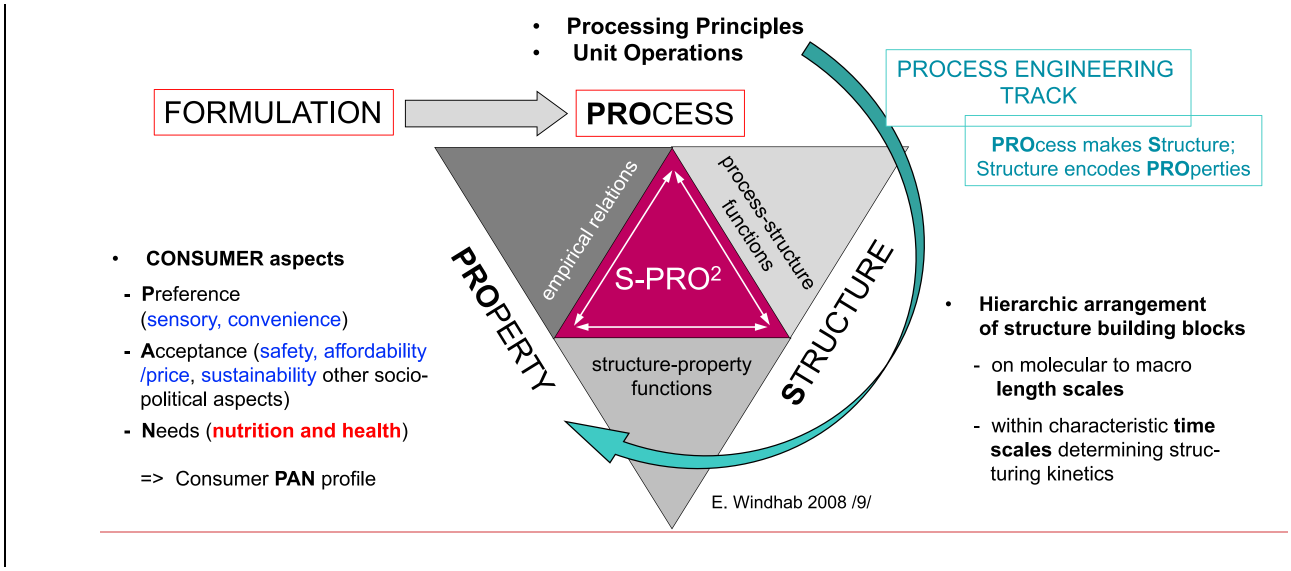

Fig. 4 | Process–Structure–Property (S-Pro²) scheme. The *Pro*cess-Structure-*Pro*perty (S-Pro²) scheme demonstrating that *Pro*cess makes Structure and Structure encodes food *Pro*perties like the nutrition value in prominent focus here[54]. The Formulation enters into the Process to be accordingly treated for generating/providing the desired properties.

creates or influences product properties must consider the food structure as a key element connecting process and properties.

This was established in the so-called *Pro*cess-Structure-*Pro*perties scheme, also denoted as the S-Pro² scheme (Fig. 4). The core message of this scheme can be briefly expressed as: "Process creates structure and structure encodes properties". Accordingly, when nutritionally relevant components within a formulation are treated in a process, that process is typically optimized to provide a processed food product structure that maintains or increases the nutritional value or at least minimizes losses in nutrient functionality with respect to digestibility, bio-accessibility, bioavailability and metabolic response.

Type and degree of processing decide the extent of structural changes and related impact on resulting properties to be tailored. In general, a Reverse Engineering approach is favoured to optimize selected food properties. This means that based on researched structure-property functions the structure which determines the optimal properties (e.g. nutrition value) is identified. This is followed by the selection of the process and adjustment of appropriate processing parameter settings according to process-structure functions derived from systematic investigations, in order to generate the identified structure representing the optimal quality characteristics intended.

In order to maintain the nutritional properties, present in food raw materials or ingredients, it may be important not to change the molecular structure of such nutrients when passing processing steps i.e. for their enrichment or separation. However, there are also cases where processing enhances digestibility, e.g. for proteins when partially denatured. Moreover, the generated or modified food matrix structure of processed foods in which the nutrients are integrated, determines their release kinetics in the digestive tract and the associated bio-accessibility and bioavailability.

The NOVA food classification system

The general reasoning for the NOVA classification system as given by its creator C. Monteiro in (ref. 10) is as follows: "*The significance of industrial processing, and in particular techniques and ingredients developed or created by modern food science and technology, on the nature of food and on the state of human health, is generally understated. This is evident in international and national policies and strategies designed to improve population nutrition and health, in dietary recommendations, and in public policies and actions guided by such recommendations. Until recently it has also been neglected in epidemiological and experimental studies concerning diet, nutrition and health*".

NOVA classifies all foods and food products into four groups as follows, with the key aspects adapted from Monteiro et al. (cited from refs. 7,8):

GROUP 1: Unprocessed and minimally processed foods. Unprocessed (or natural) foods are the edible parts of plants (such as fruit, leaves, stems, seeds and roots) or from animals (such as muscle, offal, eggs, milk), and also fungi, algae and water, after separation from nature. Minimally processed foods are natural foods altered by methods that include the removal of inedible or unwanted parts and also processes that include drying, crushing, grinding, powdering, fractioning, filtering, roasting, boiling, non-alcoholic fermentation, pasteurization, chilling, freezing, placing in containers, and vacuum packaging. The distinction between unprocessed and minimally processed foods is not especially significant.

GROUP 2: Processed culinary ingredients. Processed culinary ingredients include oils, butter, lard, sugar and salt. These are substances derived from group 1 foods or else from nature by processes such as pressing, refining, grinding, milling, and drying. Some methods used to make processed culinary ingredients are originally ancient. But now they usually are industrial products, designed to make durable products suitable for use in home, restaurant and canteen kitchens to prepare, season and cook freshly prepared dishes and meals. In isolation, processed culinary ingredients are unbalanced, being depleted in some or most nutrients. Other than salt, they are also energy-dense, at 400 or 900 kilocalories per 100 g. This is around 3–6 times more than cooked grains and around 10–20 times more than cooked vegetables. They are used in combination with foods to make palatable, diverse, nourishing and enjoyable meals and dishes such as stews, soups and broths, salads, breads, preserves, drinks, and desserts. Thus, oils are used in the cooking of grains (cereals), vegetables and legumes (pulses), and meat, and are added to salads. Table sugar is used to prepare fruit- or milk-based desserts. It is misleading to assess their nutritional significance in isolation. They should always be assessed in combination with foods.

GROUP 3: Processed foods. These include canned or bottled vegetables or legumes (pulses) preserved in brine; whole fruit preserved in syrup; tinned fish preserved in oil; some types of processed animal foods such as ham, bacon, pastrami, and smoked fish; most freshly baked breads; and simple cheeses to which salt is added. They are made by adding salt, oil, sugar or other substances from group 2 to group 1 foods. Processes include various preservation or cooking methods, and with breads and cheeses, non-alcoholic fermentation. Processing here increases the durability of group 1 foods or modifies or enhances their sensory qualities. Most processed foods have two or three ingredients and are recognizable as modified versions of group 1 foods. They are generally produced to be consumed as part of meals or dishes and also may be consumed by themselves as snacks. Most are highly palatable.

Almost all processed foods are manufactured industrially. Processes include canning and bottling using oils, sugars or salt; and methods of preservation such as salting, salt-pickling, smoking, and curing. The ingredients infiltrate the foods and so the processes alter their nature. Processed food products usually retain the basic identity and most constituents of the original food. But when excessive oil, sugar or salt are added, they become nutritionally unbalanced. Except for canned vegetables, their energy density ranges from moderate (around 150–250 kilocalories per 100 g for most processed meats), to high (around 300–400 kilocalories per 100 g for most cheeses).

GROUP 4: Ultra-processed foods. Ultra-processed foods are formulations of ingredients, mostly of exclusive industrial use, typically created by a series of industrial techniques and processes (hence 'ultra-processed'). Some common ultra-processed products are carbonated soft drinks; sweet, fatty or salty packaged snacks; candies (confectionery); mass-produced packaged bread and buns, cookies (biscuits), pastries, cakes and cake mixes; margarine and other spreads; sweetened breakfast 'cereals' and fruit yogurt and 'energy' drinks; pre-prepared meat, cheese, pasta and pizza dishes; poultry and fish 'nuggets' and 'sticks'; sausages, burgers, hot dogs and other reconstituted meat products; powdered and packaged 'instant' soups, noodles and desserts; baby formula; and many other types of product.

Processes enabling the manufacture of ultra-processed foods involve several steps and different industries. It starts with the fractioning of whole foods into substances including sugars, oils and fats, proteins, starches and fibre. These substances are often obtained from a few high-yield plant foods (such as corn, wheat, soya, cane or beet) and from puréeing or grinding animal carcasses, usually from intensive livestock farming.

Some of these substances are then subjected to hydrolysis, hydrogenation, or other chemical modifications. Subsequent processes involve the assembly of unmodified and modified food substances with little if any whole food using industrial techniques such as extrusion, moulding and pre-frying. Colours, flavours, emulsifiers and other additives are frequently added to make the final product palatable or hyper-palatable. Sophisticated and attractive packaging is used, usually made of synthetic materials. Ingredients characteristic of ultra-processed foods are either food substances of no or rare culinary use or else classes of additives whose function is to make the final product sellable, palatable and often hyper-palatable.

Food substances of no or rare culinary use, employed in the manufacture of ultra-processed foods, include varieties of sugars (fructose, high-fructose corn syrup, 'fruit juice concentrates', inverted sugar, maltodextrin, dextrose, lactose), modified oils (hydrogenated or inter-esterified oils) and sources of protein (hydrolysed proteins, soya protein isolate, gluten, casein, whey protein, and 'mechanically separated meat'). Classes of additives used only in the manufacture of ultra-processed foods, are flavours, flavour enhancers, colours, emulsifiers, emulsifying salts, artificial sweeteners, thickeners, and foaming, anti-foaming, bulking, carbonating, gelling and glazing agents. All of them, most notably flavours and colours, either disguise unpleasant sensory properties created by ingredients, processes or packaging used in the manufacture of ultra-processed foods, or give the final product intense sensory properties especially attractive to see, taste, smell and/or touch, or both.

Processes and ingredients used for the manufacture of ultra-processed foods are designed to create highly profitable products (low-cost ingredients, long shelf-life, powerfully branded). Their convenience (imperishable, ready-to-consume), hyper-palatability, and ownership by transnational corporations using pervasive advertising and promotion, give ultra-processed foods enormous market advantages. They are therefore liable to displace all other NOVA food groups and to replace freshly made regular meals and dishes, with snacking anytime, anywhere.

Identification of ultra-processed foods (UPF)

Following instructions for UPF identification were also adapted from Monteiro et al.[7,8]: "Food manufacturers do not have to state on food labels the processes used in their products, and even less the purposes of these processes. Sometimes this can make it difficult to identify ultra-processed foods with confidence. Generally, the practical way to identify if a product is ultra-processed is to check to see if its list of ingredients contains at least one item characteristic of the ultra-processed food group.

These are either food substances never or rarely used in kitchens or classes of additives whose function is to make the final product palatable or more appealing. Food substances not used in kitchens include hydrolysed proteins, soya protein isolate, gluten, casein, whey protein, 'mechanically separated meat', fructose, high-fructose corn syrup, 'fruit juice concentrate', invert sugar, maltodextrin, dextrose, lactose, soluble or insoluble fibre, hydrogenated or inter-esterified oil. The presence in the list of ingredients of one or more of these food substances identifies a product as ultra-processed.

Classes of additives exclusively used in ultra-processed foods include flavours, flavour enhancers, colours, emulsifiers, emulsifying salts, artificial sweeteners, thickeners, and anti-foaming, bulking, carbonating, foaming, gelling and glazing agents. Any example of these classes of additives, as shown on ingredients lists also identifies a product as ultra-processed" (end of cited descriptions from refs. 7,8).

Such an identification approach is largely based on food additives and little to no actual processing technologies. In addition, the list of many "industrially produced food ingredients" in the above paragraph also includes proteins and fibre, which have nutritional value in addition to other functional properties. This should be recognized as such, rather than being negatively implied as the NOVA identification puts it.

Food classification systems considering processing

The NOVA and derived NOVA-type classification systems claiming to consider processing aspects for food product classifications at the point of purchase (POP) are exemplary listed in Table 1. As described within a comprehensive comparative overview by Ch. Sadler et al.[9] these classification systems take into account qualitative conceptualization criteria, being: (a) the type of processing, (b) the intensity of processing, (c) the place of processing and (d) the purpose of processing. Figure 5 (adapted from ref. 9) schematically demonstrates these dimensions used in the conceptualization of processed foods.

C.R. Sadler et al.[9] came to the conclusion that the classification systems including the processing aspects listed in Table 1, were mostly created to study the relationship between industrial products and health. No consensus was found on what factors determine the level of food processing. The classification systems embodied socio-cultural elements and subjective terms, including home cooking and naturalness. The authors conclude that: "so far processing in the considered food classification systems is a chaotic conception, not only concerned with technical processes. Most classification systems do not include quantitative measures but, instead, imply a correlation between processing and nutrition". The authors derive that the concept of "whole food" and the role of the food matrix in relation to healthy diets needs further clarification and that the risk assessment/management of food additives also needs further debate.

NOVA ambiguities and uncertainties

As described in detail before the NOVA system sorts food products into four groups representing the "classification classes", being: group I: fresh/

Table 1 | Food classification systems developed for epidemiological studies and using processing as a criterion for categorizing consumed "processed food" (adapted from ref. 9)

No.	Abbreviation	Name/Origin	Author(s)
1	NIPH	National Institute of Public Health; Mexico	Gonzalez-Castell et al.[38]
2	IARC-EPIC	Institute Agency for Research on Cancer European Prospective Investigation into Cancer and Nutrition	Slimani et al.[39] Chajes et al.[40]
3	NOVA	Recommendation as basis for dietary guidelines.	Monteiro,[6]; Monteiro et al.[8]; Moubarac et al.[41]; Schnabel et al.[42]
4	IFPRI	International Food Policy Research Institute in Guatemala	Asfaw[43]; Moubarac et al.[44]
5	IFIC	International Food Information Council	Eicher-Miller et al.[45,46]
6	NUPENS-USP	Nucléo de pesquisas Epidemiologicas em Nutricao e Saude; Univ. de Sao Paulo	de Costa Louzada et al.[47]
7	POTI	Department of Nutrition, Carolina Population Center, University of North Carolina, USA	Poti et al.[48]
8	SIGA	Siga, une approche holistique de la qualité en alimentation	Fardet[49]; Siga[50]

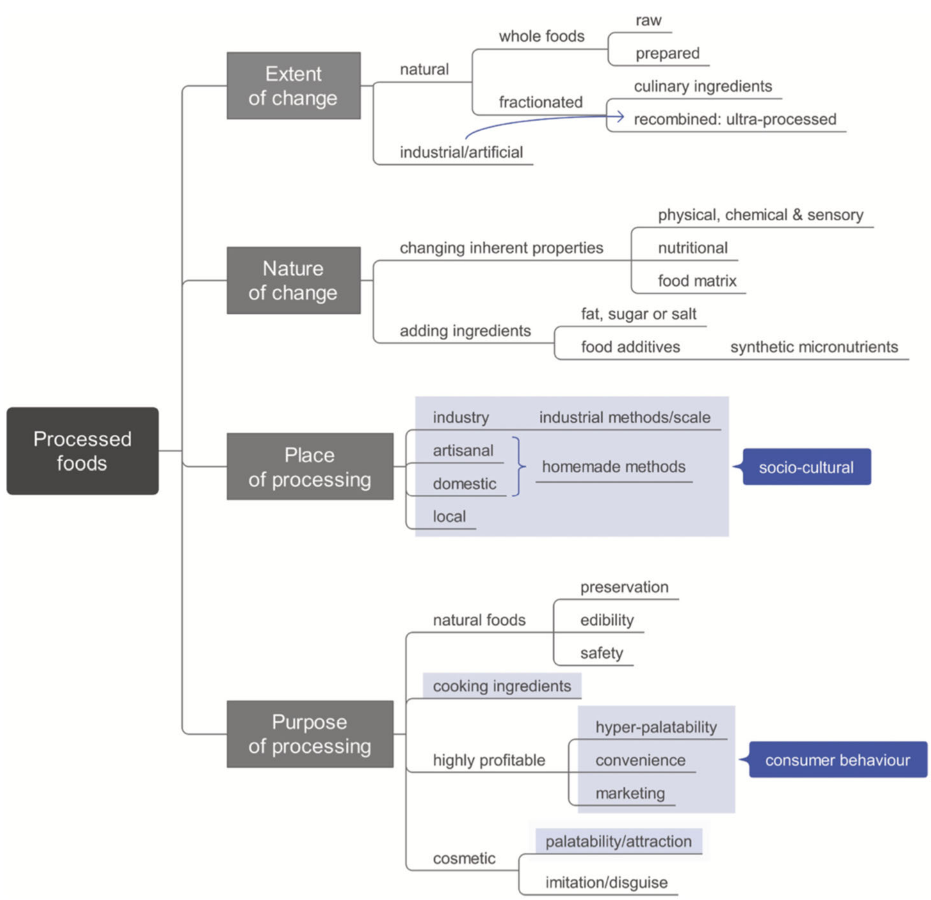

Fig. 5 | Processed food conceptualization dimensions. Categorization of processing in the NOVA/NOVA-type food classifications according to Ch. Sadler (adapted from Ch. Sadler et al.[9] with author and Copyright permission).

minimally processed food; group II: processed ingredients; group III: processed food and group IV: ultra-processed food.

Both, the conceptualization dimensions and the NOVA group/class designations give the impression that from group I to group IV some degree of processing or processing intensity is increasing. However, the expectation that an assignable level of processing underlies the distinction of the NOVA classification groups is not met. In addition, and contrary to the expectation created, the main classification parameters (CPs) applied by the NOVA system to sort into the groups/classes I–IV marked with processing levels, follow the formulation-based addition of sugar, salt, saturated fats and ingredients of mostly exclusive industrial use. It is worth noting that most authoritative food-based dietary guidelines already include recommendations, including quantitative limitations, on foods, nutrients and food components to limit based on such formulation-based criteria.

Obviously, the ingredient composition for a food product is a matter of formulation and not of processing. Moreover, compared with proper formulation rules the NOVA system does not quantify group/class (I–IV) specific fraction ranges of the "critical" ingredients. Based on such formulation-determined but processing designated food product groups or classes I–IV, the NOVA system derives correlations between consumption of food products from these groups/classes (I–IV) with results from observational studies about obesity and health risks. This approach is not evidence-based and is not clear and incomplete.

For the IUFoST task force on Processing for Nutrition, Diet and Health the inclusion of processed food impact correlations with obesity and health risk outcomes was not intended. On the other hand, the stated aim of the task force was to create a more solid basis for the correlations intended by NOVA using a quantitative consideration of the processing influence on the nutritional quality of processed food products.

In this context, the following issues (1–10) with the NOVA/NOVA-type classification systems have been identified by the task force. The key aspects 1 and 2, to be avoided in food classification development and derived applications were selected for further detailed exploration.

1. Confusion in the use of formulation and processing terms
2. Lack of quantification of processing level
3. Weak scientific approach
4. Conflicting issues with nutritional advice
5. Conflicting issues with fortified and personalized food
6. Inadequacy with the needs of developing countries
7. Differences in ingredients and food products
8. Multifaceted complex non-linear relationships
9. Ambitious terminology used (NOVA)
10. Processing misinterpreted as negative factor

Since the task force is of the opinion that the NOVA system has included processing as a significant influencing factor on the nutritional properties of processed food products in the classification of such products which has so far not been sufficiently considered, the following questions should be further examined and evaluated in order to propose and develop possible refinement and optimization solutions:

Question A: How can the main issues of the NOVA system recognized by the task force being (i) the confusion in using formulation and processing terms and (ii) the lack of quantification of formulation and processing levels, be tackled by the task force?

Question B: Which are the benefits or weaknesses of the NOVA classification system compared to existing systems of nutrient profiling and derived recommendations for dietary guidelines in the view of renowned experts in the field outside of the task force?

Question B is addressed in the next chapter. Question A concerns the main theme of the task assigned to the IUFoST Task Force, which is dealt with in very detail in the chapter after the following.

Dietary guidelines and NOVA

This chapter is meant to address question B posed before. As a part of the analysis of food classification systems, the task force also reviewed a number of recent publications that addressed the NOVA classification system and evaluated its claimed added value compared with so far successfully applied nutrient profiling of food products for dietary guideline recommendations[11–18]. Some of the prominent experts in the human nutrition field are reflected by citations of their statements in the following.

OPINION 1: In a debate between Astrup, A. & Monteiro, C. A. published in *Am. J. Clin. Nutr.* **116**, 1482–1488 (2022)[11],

A. Astrup comes to the conclusion that: "The NOVA classification of ultra-processed foods (UPFs) rests on poorly defined food processes and the presence of food additives from a chemically heterogeneous group, easily leading to misclassification. UPFs are claimed to promote overconsumption of energy and obesity due to high palatability, but little evidence supports effects beyond those that can be accounted for by nutrient composition, energy density, and food matrices. Observational studies link dietary intake of UPFs with obesity, but none have demonstrated independent associations after controlling for likely confounders. A highly cited randomized controlled feeding study that compared a UPF diet with an unprocessed diet showed a rapidly weaning effect on energy intake that can be entirely explained by more conventional and quantifiable dietary factors, including energy density, intrinsic fibre, glycemic load, and added sugar. Clearly, many aspects of food processing can affect health outcomes, but conflating them into the notion of ultra-processing is unnecessary because the main determinants of chronic disease risk are already captured by existing nutrient profiling systems. In conclusion, the Nova classification adds little to existing nutrient profiling systems; characterizes several healthy, nutrient-dense foods as unhealthy; and is counterproductive to solve the major global food production challenges".

C.A. Monteiro responded that: "The concept of ultra-processing, as contained within the NOVA food classification system, is well-founded, clear, supported by a wealth of investigations, and crucial to inform new dietary guidelines and other public policies and actions designed to reduce the production and consumption of ultra-processed foods". For further detail on the description of the NOVA classification system in this report refer to the sub-chapters "The Nova Food classification" and "Identification of ultra-processed foods (UPF)" described above.

OPINION 2: by Drewnowski, A., Gupta, S. & Darmon, N. in *Nutr. Today* **55**, March/April (2020)[12] stated:

"The category of "ultra-processed" foods in the NOVA food classification scheme is ostensibly based on industrial processing. We compared NOVA category assignments with the pre-existing family of Nutrient Rich Food (NRF) indices, first developed in 2004. The NRF indices are composed of 2 sub-scores: the positive NR based on protein, fibre, vitamins and minerals, and the negative LIM sub-score based on saturated fat, added sugars, and sodium. The 378 foods that were components of the widely used Fred Hutchinson Cancer Center food frequency questionnaire were assigned to NOVA categories and scored using multiple NRF indices. Contrary to published claims, NOVA was largely based on the foods' content of saturated fat, added sugars, and sodium. There were strong similarities between NOVA categories and NRF scores that were largely driven by the nutrients to limit. Nutrient density led to higher increased NRF scores but had less impact on NOVA categories. As a result, the NOVA scheme misclassified some nutrient-rich foods. We conclude that the NOVA classification scheme adds little to the pre-existing nutrient profiling models. The purported links between NOVA categories and health outcomes could have been obtained using pre-existing NRFn.3 nutrient density metrics."

OPINION 3: by Hess, J. M. et al. in *J. Nutr.* **153**, 2472–2481 (2023)[13]:

"The purpose of this proof-of-concept study was to determine the feasibility of building a menu that aligns with recommendations for a healthy dietary pattern from the 2020 DGA and includes 80% kcal from UPF as defined by NOVA. In the ultra-processed DGA menu that was created, 91% of kcal were from UPF, or NOVA category 4. The HEI-2015 score was 86 out of a possible 100 points. This sample menu did not achieve a perfect score due primarily to excess sodium and an insufficient amount of whole grains. This menu provided adequate amounts of all macro- and micronutrients except vitamin D, vitamin E, and choline. The authors conclude that: "Healthy dietary patterns can include most of their energy from UPF, still receive a high diet quality score, and contain adequate amounts of most macro- and micronutrients.

OPINION 4: by Braesco, V. et al. in Europ. *J. Clin. Nutr.* **76**, 1245–1253 (2022)[14]: "French food and nutrition specialists completed an online survey in which they assigned foods to NOVA groups. The survey comprised two lists: one with 120 marketed food products with ingredient information and one with 111 generic food items without ingredient information. We quantified assignment consistency among evaluators using Fleiss' κ (range: 0–1, where 1 = 100% agreement). Hierarchical clustering on principal components identified clusters of foods with similar distributions of NOVA assignments. There were three clusters within the marketed foods: one contained 90 foods largely assigned to NOVA 4 (91% of assignments), while the two others displayed greater assignment heterogeneity. There were four clusters within the generic foods: three clusters contained foods mostly assigned to a single NOVA group (69–79% of assignments), and the fourth cluster comprised 28 foods whose assignments were more evenly distributed across the four NOVA groups.

Conclusions: Although assignments were more consistent for some foods than others, overall consistency among evaluators was low, even when ingredient information was available. These results suggest current NOVA criteria do not allow for robust and functional food assignments."

From these human nutrition expert opinions cited before and a larger number of publications not cited here, the IUFoST task force could conclude that the NOVA classification in summary has also weaknesses concerning:

B1. Only little to no addition to existing nutrient profiling systems

B2. Not evidence-based statements on the harmfulness of approved processes/additives & their health risk impact

Additional information of relevance for the task force which could be gleaned from literature /e.g. ref. 11 was, that there is strong opinion in the scientific community on:

B3. The extent of food processing significantly affects diet quality and health outcomes.

B4. Classification systems based on certain characteristics of food processing, including the degree to which the food matrix is affected and the use of certain additives, can distinguish categories of food with beneficial or adverse health outcomes in a useful manner.

While answers B1 and B2 should be addressed in the context of recommendations to be worked out by the task force, B3 and B4 additionally confirm the relevance of processing as a main influential factor to be considered in future food classification and the necessity of further research on the mentioned aspects.

Differentiation of formulation and processing in food classification by definition and quantification

Within this key chapter of the report, question A posed at the end of the previous chapter will be prominently addressed, which for making reading easier is repeated here being: "How can the main issues of the NOVA system recognized by the task force being (i) the confusion in using of formulation and processing terms and (ii) the lack of quantification of a processing degree, be tackled?"

Formulation (F) and Processing (P) were identified as independent but interacting factors in the food product manufacture, in order to optimize desirable food properties of relevance according to consumers Preference, Acceptance and Needs (PAN profiles[19]). Such property characteristics as mentioned before, are: nutrition value (*task force focus*), safety, palatability (sensory characteristics), sustainability, convenience and affordability to which F & P can contribute in a positively complementing or counteracting manner. Accordingly, it was stated that Formulation and Processing have to be treated as separate criteria if introduced into food classification systems and should consider quantitative parameters to express their specific "levels of execution".

The following DEFINITIONS were decided by the task force:

Formulation: "Systematic selection of relative quantities of ingredients for a food product"

Processing: "Treatment of a food material to achieve a desired effect"

Enabling a quantitative approach to describe the influence of formulation and processing of a food product on a targeted food property, the latter has to be decided in the context of the question to be answered or the problem to be solved. If Food classification aims for supporting the development of dietary guidelines the nutrition value (NV) of a food product is confirmed as a key property. In the following a suggested 3-STEP PROCEDURE (3SP) is described for processed food products, treating formulation and processing separately but taking into account their mutual influence on the NV.

For quantification of the nutrition value (STEP 1), the so-far well-experienced Nutrition Rich Food Index (NRF*x.y*) was selected as the exemplary approach[1,20,21]. The NRF*x.y* is a formulation-related value for nutrition profiling of food products considering the two groups of *x* recommended nutrients (NR) and *y* nutrients to be limited (LIM) according to Eq. (1), below[1]. Typical numbers for *x* and *y* are 9 and 3 according to 9 recommended nutrients (NR): protein, dietary fibre, vitamin A, vitamin C, vitamin E, calcium, iron, potassium and magnesium and 3 nutrients to be limited (LIM): added sugar, sodium and saturated fatty acids.

$$\mathrm{NRF9.3_{100kcal}} = \mathrm{NR9_{100kcal}} - \mathrm{LIM_{100kcal}} \quad (1)$$

with: (I) $\mathrm{NR9}_{100\ \mathrm{kcal}} = \Sigma_{1-9}\ (m_{\mathrm{nutrient}\ i}/m_{\mathrm{DV}i})/S_i \cdot 100$ denoting 9 nutrients recommended per product portion providing 100 kcal (418.4 kJ) of energy, $m_{\mathrm{DV}i}$ = mass of Daily Value (nutrient *i*) and S_i = calories per serving

(ii) $\mathrm{LIM3}_{100\ \mathrm{kcal}} = \Sigma_{1-3}\ (m_{\mathrm{nutrient}\ i}/m_{\mathrm{MRV}i})/S_i \cdot 100$ denoting (3) nutrients to be limited per product portion providing 100 kcal (418.4 kJ) of energy, $m_{\mathrm{MRV}i}$ = mass of maximum recommended value.

A logical connection can be seen between nutrient density (ND), energy density (ED) and NRF, since for the basis of a food portion with 100 kcal energy content, only products with high ND or high ED and high ND achieve a high NRF score. Those with (only) high ED or low ND are found in the low NRF score range. NRF*x.y* also has strengths in terms of its flexible adaptability to the preferred needs of certain consumer groups, as explained in more detail in the Supplementary Information to this report. Consequently, NRF*x.y* was chosen as the recommended quantitative base definition of nutritional value, the selected food property to be classified here.

Within STEP 2 of the 3SP the quantification of degrees of formulation and processing is treated. Since the NRF*x.y* describes the proportions of the nutritionally relevant components of a food formulation, it also represents a nutritional value-related "formulation level" that can be used as a formulation classification parameter (CP). In order to define an equally suitable, easy-to-determine processing parameter, it is suggested to refer to the chosen NRF*x.y*-based nutrition value definition and express the "degree of processing" by the difference in the NRF*x.y* value after and before a processing treatment, denoted as ΔNRF*x.y*. which is subsequently used to classify the influence of processing on the nutrition value (Eq. (2)).

$$\Delta\mathrm{NRFx.y} = \mathrm{NRFx.y_{after\ processing}} - \mathrm{NRFx.y_{before\ processing}} \quad (2)$$

The values *x* (number of nutrients recommended) and *y* (number of nutrients to be limited) were chosen as 9 and 3, thus configurating the NRF9.3 as has been described before.

The graphical representation of the IUFoST F&P Classification (abbreviated as IF&PC) approach is denoted as STEP 3 of the 3SP. Within this, a 2D-(F&P) Classification Matrix Diagram (CMD) is suggested for illustrating (i) the NRF9.3 as quantitative nutrition value-related "formulation level" classification parameter (CP1, *x*-axis) and (ii) **Δ**NRF9.3 as quantitative nutrition value-related "processing level" classification parameter (CP2, *y*-axis) generally demonstrated in Fig. 6 and complemented with data from processed food systems ([22] and USDA-FNDDS[23]) in Fig. 7. Figure 6 restricts to demonstrate shifts in positioning of a food system depending on principle changes in formulation or processing.

On the *x*-axis of Figs. 6 and 7 the NRF9.3 is displayed within the range of −100 to +200. Fresh berries and citrus fruits come close to NRF9.3 values of 200 while sugar-sweetened soda beverages can reach values below −50[6]. The processing degree ΔNRF9.3 can impact positively or negatively on the nutrition value within an estimated range of −100 to +100 based on initial experience. The coupled impact of formulation level (F) expressed by NRF9.3 and processing level (P) expressed by ΔNRF9.3 can be calculated by applying Eq. (3) which defines the so-denoted Formulation and Processing Food Index $\mathrm{FPFI^N}$, the superscript N indicating the nutrition value as the considered food property being classified. Thus, $\mathrm{FPFI^N}$ values represent quantitative Nutrition Value classes, the magnitude of which is indicated in Figs. 6 and 7 by the Iso-$\mathrm{FPFI^N}$ lines (lines of constant $\mathrm{FPFI^N}$).

$$\mathrm{FPFI^N} = [(\mathrm{NRF9.3_1} + 2\Delta\mathrm{NRF9.3})/\mathrm{A}] - \mathrm{B} \quad (3)$$

A, *B* denoting scaling constants of the Classification Matrix Diagram (CMD) demonstrated in Figs. 6 and 7, where *A* = 25 (1 $\mathrm{FPFI^N}$ unit equivalency to 25 NRF9.3 units) and *B* = −2 ($\mathrm{FPFI^N}$ value in the origo). The subscript 1 represents the NRF9.3 before the considered processing step)

Tracking of formulation and processing in the classification matrix diagram (CMD)

Points located in the CMD are denoted as P_i (x_i/y_i) or P_i ($\mathrm{NRF9.3}_i/\Delta\mathrm{NRF9.3}_i$), with NRF9.3 being the *x*-coordinate and ΔNRF9.3 the *y*-

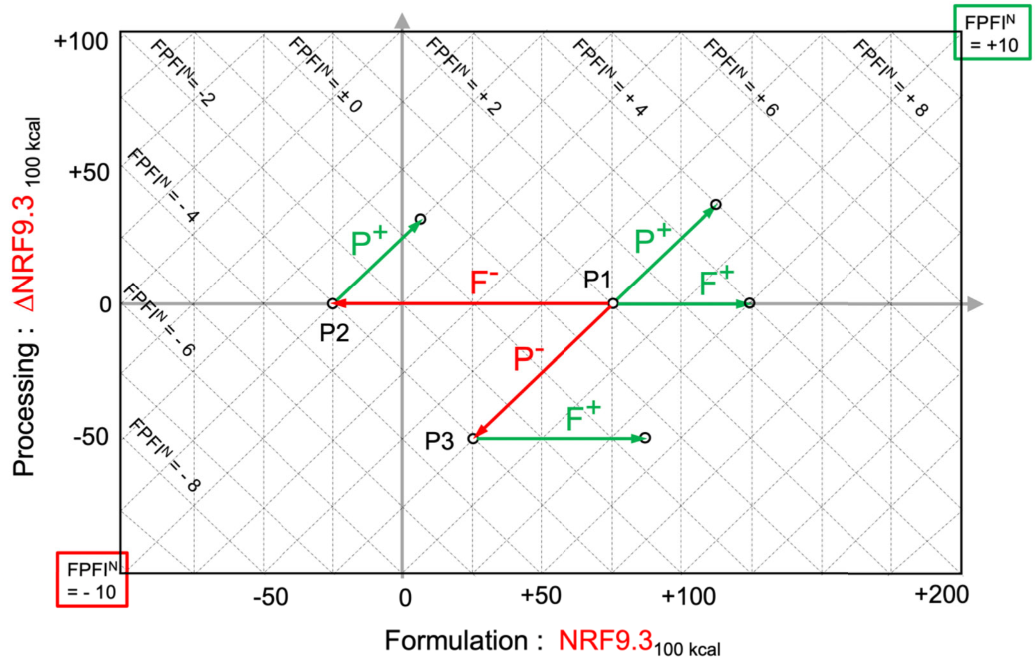

Fig. 6 | Formulation and processing Classification Matrix Diagram (CMD). 2D-(F&P) Classification Matrix Diagram (CMD) illustrating the Formulation (NRF9.3) and Processing (ΔNRF9.3) classification parameter space with introduced Formulation and Processing Food Index $FPFI^N$ and Iso-$FPFI^N$-lines (definition by Eq. (3)), scaled from −10 to +10, enabling re-dimensioned $FPFI^N$-one-parameter classification based on the coupled quantitative impacts of formulation (F) and processing (P) measures. - Shifts in CMD-positioning of food systems in positive or negative directions (i) for formulation (F) changes, indicated by horizontal F^+(green) or F^-(red) vectors, (ii) for processing (P) impacts, indicated by P^+(green) or P^-(red) vectors along +45° inclined straight lines.

coordinate. A formulation for a food product to be processed before processing is described by a starting point P_1 ($NRF9.3_1$/0). This starting point P_1 is located on the ΔNRF9.3 (processing scale) zero line. If a pure formulation change is executed (e.g by adding sugar to glaze carrots; see example in Fig. 7), this causes a horizontal shift from P_1 ($NRF9.3_1$/0), to a P_2 ($NRF9.3_2$/0) in the diagram. With $NRF9.3_2 < NRF9.3_1$ due to the LIM-term increase in the NRF9.3 caused by the sugar addition (see Eq. (1)), the shift vector (arrow) is negatively directed. - Subsequent designations of indices for points in the CMD refer specifically to Fig. 7.

A processing step that results in a change of the NRF9.3 value from $(NRF9.3)_2$ before processing to $(NRF9.3)_3$ after processing and thus generates a corresponding ΔNRF9.3 (=$(NRF9.3)_3-(NRF9.3)_2$), causes a point shift from the starting point P_2 ($NRF9.3_2$/0) to the resulting P_3 ($NRF9.3_2$ + ΔNRF9.3/$ΔNRF9.3_3$). Thus, P_3 is placed along a straight line (SL) through P_2 inclined (for equidistant scaling units in x and y direction by +45°) relative to the NRF9.3 (x) axis (Fig. 6). If $NRF9.3_2 > NRF9.3_3$ then ΔNRF9.3 < 0, a negative impact of the processing step is resulting (see example: glazed carrots cooked; Fig. 7), and P_3 is lower left-shifted from P_2 along SL. In the case of $NRF9.3_2 < NRF_3$ the P_3 shift will be to the upper right along SL (see example, pea protein isolate processing from pea seeds; Fig. 7).

For each change in formulation or processing the $FPFI^N$ can be calculated according to Eq. (3). Respective $FPFI^N$ values are denoted for the exemplary processed product examples presented within Fig. 7.

The $FPFI^N$ value shifts between starting- and endpoints correspond to the influence of coupled formulation and processing steps applied in the manufacture of a processed food product one can stepwise follow in the CMD. Which $FPFI^N$ value (class) a finally processed food product reaches also depends on the starting point, given by the NRF9.3 of the initial formulation. Starting from base formulations of different NRF*x.y* (Nutrition Value) and coupling with different processing steps of positive or negative impact could lead to endpoints in the CMD of similar $FPFI^N$ values and thus in the same F&P-coupled nutrition value class. A detailed interpretation of such results will also depend on the applied extensions to the NRF9.3 as suggested in the Supplementary Material method 1.2.

The $FPFI^N$ values scale from −10 to +10. $FPFI^N{}_i$ and can be calculated according to Eq. 3 for each point P_i in the CMD. Iso-$FPFI^N$ lines have been inserted into the CMD for orientation. These Iso-lines are inclined by −45° to the NRF9.3-axis (for equidistant scaling of both CMD axes) thus being oriented rectangular to the straight SL-lines along which the "processing impact vectors" with a length of $\sqrt{2}$ ΔNRF9.3 are displayed. The factor $\sqrt{2}$ results from the fact that the processing vector endpoint (e.g. P_3 in Fig. 7) is received from equal shifts of the starting point (e.g. P_2) by ΔNRF9.3 = $(NRF9.3)_3$ - $(NRF9.3)_2$) into the x and y directions. For each processing change resulting in a ΔNRF value and related point shift in the diagram from P_i to P_{i+1} the $FPFI^N$ in the endpoint P_{i+1} is received from Eq. (3) (for further extended details see Supplementary Method 1.2).

Discussion

Key benefits in applying the IF&PC scheme

The CMD has been created in order to support the practical application of the two separated and quantified levels of formulation (F) and processing (P) impacts on the nutrition value (NV). As expected, such quantifying two-parameter classification system initially places increased demands on handling compared to only qualitatively descriptive or partially quantifying single-parameter systems.

As the exemplary (apple, carrot and pea) demonstration of formulation changes and processing modifications in Fig. 7 indicates, practical handling for the two-parameter IF&PC approach can be well assisted by the CMD. Moreover, the quantitative F&P coupling parameter $FPFI^N$ (Food Processing and Formulation Index) as depicted in the CMD indicates a simplified base for possible future consumer communication and product labelling approaches considering quantitative F and P aspects appropriately. For assistance in refining the NOVA classification systems, it may be advantageous to apply the NRF9.3 (or

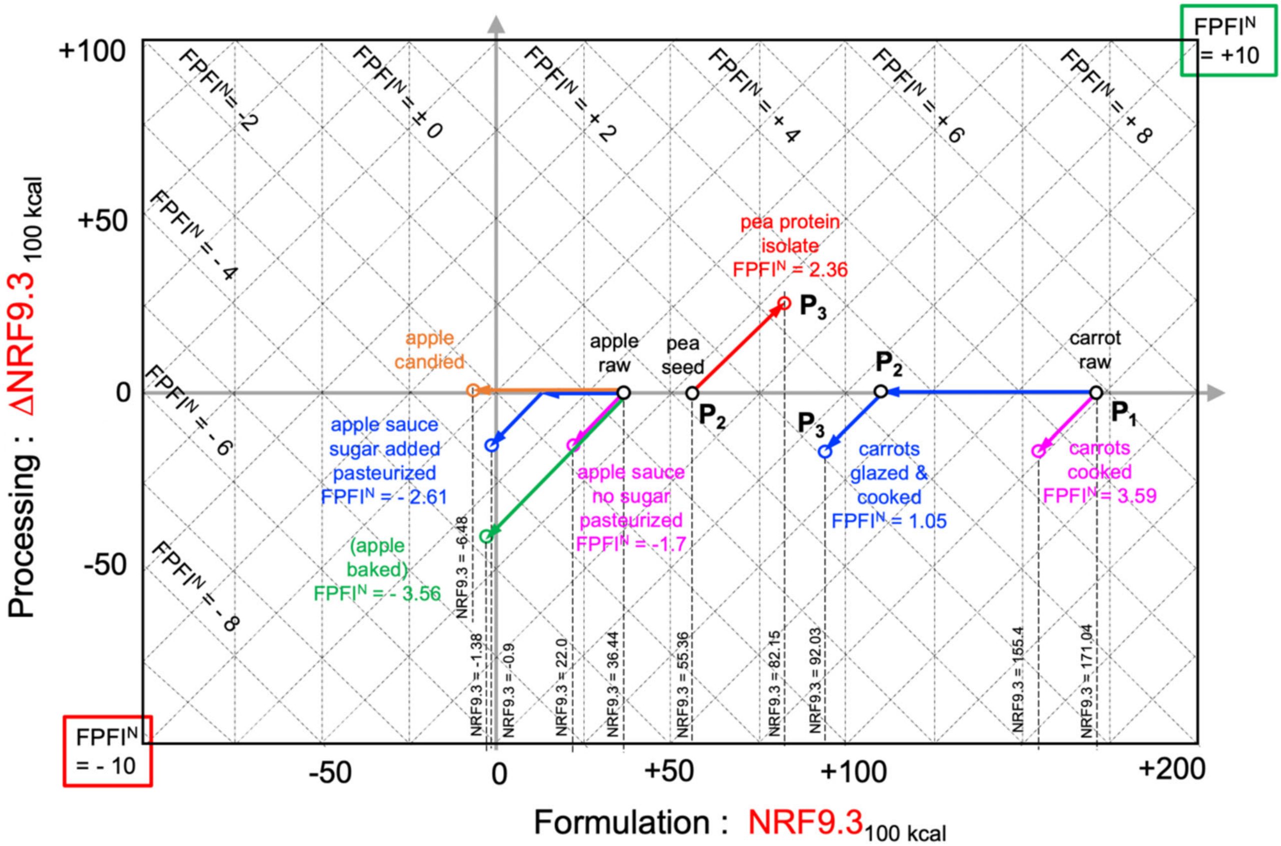

Fig. 7 | Exemplary formulation and processing impacts on food products represented in the Classification Matrix Diagram (CMD). Examples of processed foods (apple, carrot and pea products) represented in the Classification Matrix Diagram (CMD), including calculated FPFI^N-values (data sources: FNDDS[23] and[22]); pea protein isolate processing (red arrow) from pea seeds (e.g. by alkaline extraction and isoelectric precipitation) shows an increase in FPFI^N mainly due to the factor 3.5 concentration of protein[55]; other considered processes (pasteurization, baking, cooking) demonstrate FPFI^N-reduction due to losses in vitamins.

Table 2 | Handling rules and determined parameter info by the CMD application

No.	Criterion	Handling	Benefits (CMD)
1	Starting with a formulation	Calculate the NRF9.3$_1$ and place starting point P$_1$ (NRF9.3$_1$/0) on the ΔNRF9.3 zero line	Initial formulation-based nutrition value determined and visualized
2	Pure formulation change	Calculate new NRF9.3$_2$ and insert point P$_2$ (NRF9.3$_2$/0) on the ΔNRF9.3 zero line.	Horizontal shift from P$_1$ to P$_2$ on ΔNRF9.3 zero line indicates the nutrition quality change due to the formulation modification
3	Processing treatment application	Calculate ΔNRF9.3, insert point P$_3$ (NRF9.3$_3$/ΔNRF9.3) in CMD and calculate FPFI^N by Eq. (3)	Shift length ($\sqrt{2}$ ΔNRF9.3) of P$_2$ to P$_3$ along $+45°$ inclined line (SL) through P$_2$; denotes the processing impact on NV Resulting FPFI^N indicates the coupled formulation and processsing impact on the nutrition value NV

modifications of it introduced as NRF*$x.y.z$ in Supplementary Information to this report) as quantitative formulation characteristics and ΔNRF9.3 (or respective modifications ΔNRF*$x.y.z$) separately, or in the coupled FPFI^N format, for the NOVA-specific correlations with obesity and related health risk outcomes. Main handling rules and resulting benefits in applying the CMD are summarized in Table 2.

Extension of the IF&PC application frame

There is a range of desirable extensions of the IUFoST Formulation & Processing Classification (IF&PC) approach. These concern aspects of (a) considering other or further nutrients, (b) weighing nutrients included in the NRF$x.y$ differently, (c) including additional nutrients or nutrient groups which are influenced by processing treatments leading to their reduction or increase and (d) introduce additional food matrix function criteria of nutritional relevance which may also be influenced by processing. In Table 3 a detailed overview of these extension aspects (a–d) is given, including contextual measures taken, being under exploration or of future research interest.

A more detailed overview of IF&PC-based extensions on application scenarios for different consumer groups and additional categories of processing treatments is given in Supplementary Information to this report.

The exploration of relevant formulation and processing step combinations is expected to complement part of future project work for refinement and validation of the introduced IUFoST Formulation and Processing Classification (IF&PC) scheme with its integrated 2D-(F&P) Classification Matrix Diagram (CMD) tool. Main future requirements will be (i) the acquisition of nutrient data for ingredients and food component mixtures before and after different processing as well as (ii) the identification of processes or processing steps to be specifically considered in the classification. Related challenges and opportunities are expected in this context for modified definitions of the NRF to extend the application range of the IF&PC approach (see Supplementary Method 1.2 to this report).

Table 3 | Suggested extensions of the IF&PC scheme & expected measures/benefits concerning a more holistic description of F& P impacts on the nutrition value (NV)

No.	Extension-Aspect	Suggested considerations	Expected benefits (CMD)
(a)	Wider ranges of nutrients are recommended (NR) and to be limited (LIM)	Extending the NRF9.3 to NR ($x > 9$), LIM ($y > 3$); partially already applied e.g. in ref. 51)	Improved fit for consumer groups with specific nutrient requirements
(b)	Different weighing of specific nutrients/nutrient groups (NR, LIM)	Giving different weights to specific nutrients by introducing nutrient or nutrient group (NR, LIM) specific weighing factors a_i into the NRF*x.y* (addressed by some authors e.g. ref. 52)	Adaptability for consumer groups or individuals (personalization) with specific nutrient requirements
(c)	Consideration of ingredients/components of relevant impact on the nutrition value (NV) which can be influenced (reduced or activated/generated) by processing	Inclusion of the groups of: (z_1) antinutrients to be inactivated (i.e.: phytate, tannins, trypsin inhibitor, polyphenols) (z_2) contaminants to be extracted or neutralized (z_3) components to be treated for improving their digestibility (i.e. proteins, starches, etc.) To follow the suggested IF&PC scheme approach such components/ingredient groups will have to be represented in the NRF$x.y.z_1…z_N$ and the related ΔNRF$x.y.z_1…z_N$ and being determined by analyses before and after processing steps (suggested & conceptually pre-explored by IUFoST task force, Supplementary Method 1.2)	Processing-induced reduction of $z_1…z_N$ components (e.g. antinutrients) will enable improving the nutrition value (increase in modified NRF$x.y.z_1…z_N$). This will enter into a negative term within NRF$x.y.z_1…z_N$ and ΔNRF$x.y.z_{1…}z_N$, with the z_i-component reduction increasing these. Thus, in a CMD the calculated ΔNRF*x.y.z* processing vector would be directed upper-right along a +45° oriented straight line (SL) relative to the *x*-(NRF*x.y.z*) axis. The FPFI^N of the endpoint in the CMD is shifted towards increased values ("green zone" directed). This is expected to enable the demonstration of a series of positive processing impact mechanisms relevant for the NV.
(d)	Consideration of food Matrix effects on digestion and nutrient release kinetics	(z_4) Introduction of a kinetics factor term as processing dependent weighing factor for nutrients the release kinetics of which is of relevance for digestibility, bio-accessibility & bioavailability as well as e.g. for related satiation kinetics. (suggested by IUFoST task-force, according to supplementary Method 1.2.	This is expected to newly add kinetics aspects into nutrition value (NV) description. It is seen as crucial if eating and digestion-related phenomena shall be taken into account which are time-dependent In the context of this report, the food uptake kinetics (eating speed/frequency) & its relation to digestion and "satiation" kinetics is of major interest to better understand consumers' "overeating" behaviour, a key factor for obesity and related health risk outcomes. Research and development work in this thematic domain is highly recommended.

Table 4 | NOVA analysis-based identification of refinement measures

No.	Ambiguities/inaccuracies	NOVA-intrinsic sources	Suggested measures
1	Confusion of formulation and processing	S1. Discrepancy between nature of classification parameters and the designation of classes S2. Vague and over-inclusive definition of UPF S3. No clear focus on nutrition value (e.g for specific "UPF-ingredients")	M1. Clear definition, differentiation & separation of formulation & processing M2. Reference to nutrition value as 1st target property for M1 measures M3. In future: consider formulation & processing parameter(s) impact on palatability & satiation kinetics aspects as 2nd/3rd target properties (including aspects of e.g.: matrix volume, water & air content, H_2O-binding in modified NRF*)
2	Missing quantification of formulation and processing parameters	S4. Restriction to the qualitative characterization of food products (no thresholds for formulation, no levels of formulation and processing)	M4. quantifying levels of formulation (i.e. NRF**x.y.z*) & processing (i.e. ΔNRF**x.y.z*) M5. enabling coupling of F- & P-parameters (e.g. FPFI^N) to simplify M6. in the future: consideration of (i) matrix volume & water/air fractions incl. their change by processing (e.g drying/aeration/gelling); (ii) gastro-intestinal rheology
3	Weak evidence base (observational studies) for correlations between food classes & obesity/CNND disease risks	S5. No clear control of other risk factors for weight gain S6. Risk of misclassification (i.e. single ingredient dependency for UPF)	M7. Base correlations with obesity & health risks on quantified F&P parameters taking nutrition value (& prospectively satiation kinetics) into account

Recommendations for NOVA refinement

This chapter is meant to extract part of the toolbox elements that have been developed by the IUFoST task force for differentiation and quantification of formulation and processing impacts on the nutrition value, in order to suggest the application of such elements for refinement of the NOVA classification system. In this context further exemplary literature supporting the NOVA classification (e.g. refs. 24–29) and such that takes a critical position (e.g. refs. 30–35) is considered.

The proposed steps to refine the NOVA classification system aim to eliminate ambiguities and inaccuracies that were identified by the task force and further analysed, with regard to their NOVA-based causes. Table 4 provides an overview of the results of these analyses and the proposed measures derived from these, including conclusions derived from the nutrition experts' opinions considered in the chapter denoted as "Dietary Guidelines and NOVA" before[11–14].

In Table 4 (column 3) refinement measures for the NOVA classification system are listed to tackle the identified ambiguities and inaccuracies in the "NOVA Ambiguities and uncertainties" chapter of this report repeated in abbreviated form (as M1 to M7).

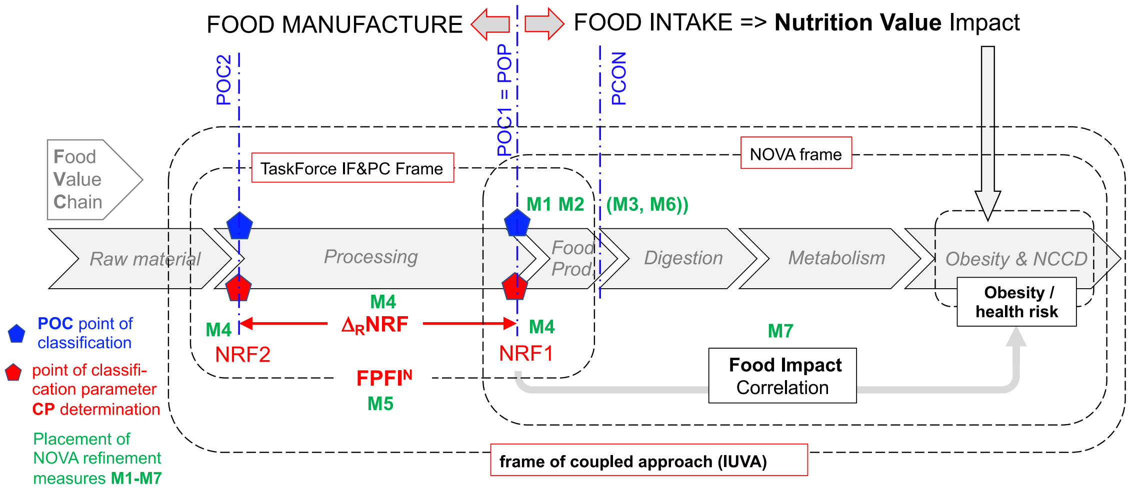

Fig. 8 | Refining of the NOVA system by suggested IF&PC system approach. NOVA system refinement suggestion applying the suggested IF&PC system approach to a classification system taking differentiated and quantified formulation and processing parameter impacts on the Nutrition Value into account, based on which the NOVA correlations with obesity and health risk outcomes could be improved; positioning of suggested NOVA refinement measures M1–M7 (Table 4) within a hypothetical coupled IF&PC & NOVA (IUVA) approach (prospective measures in brackets).

For the suggested refinement measures presented in column 3 of Table 4 the base for measures M1, M2, M4 and M5 is described by the IF&PC scheme as explored before in this report. Measures M3 and M6 of future perspective concern suggested 2nd (and/or 3rd) properties besides the nutrition value to be considered. Since the NOVA classification system reasons strongly about the palatability of a food product and related overeating by the consumer, the "Satiation Kinetics Potential (SKP)" is recommended as such 2nd target property. A related parameter relevant for consideration in the modified NRF**x.y.z* could be the calorie-specific food matrix volume. This is strongly dependent on (i) water content and water binding characteristics of the food product which in turn is expected to significantly influence the filling degree and residence time in the gastric volume upon eating as well as (ii) on the rheology of the gastric content. NRF*x.y.z could consider a related volume-parameter term and processing can largely impact on such, e.g by drying or concentration (volume and water content reduction) or by water incorporation supported by gelling/thickening (volume and water content/water binding increase).

This is an attempt of suitable parameter selection but is still far from comprehensively covering the satiation/overeating/obesity relationships in all their complexity. However, this approach can be seen as a first prospective step towards the extended application of the IF&PC scheme for another target property (Satiation Kinetics Potential) of processed foods, which, in addition to the nutrition value (NV) influences obesity and related health risks. This approach could therefore be understood as a future complementary step in a refinement procedure for the NOVA classification system using the IF&PC scheme as an efficient tool.

Hence, the IF&PC scheme would enable refining the NOVA classification base at the point of purchase (POP) based on which supporters of an accordingly refined NOVA system could then build an intended food impact correlation with obesity and related health risk data. NRF**x.y.z* for the formulation level and ΔNRF**x.y.z* for the processing level or FPFI^N as recoupled formulation and processing level would thus be applied as quantitative classification base parameters. Such synergistic IF&PC-NOVA connection denoted here as suggested IUFoST- refined NOVA (IUVA) approach is schematically demonstrated in Fig. 8.

Summarizing this chapter, the IUFoST task force is of the opinion that the application of the IF&PC scheme will have the potential to bring the following improvements to the NOVA system, which will, in turn, assist in eliminating major ambiguities and uncertainties that exist up to now:

(1) Clear separation of formulation and processing influences on the nutritional value of processed foods which can be optimized separately.
(2) Quantification of levels of formulation and processing impacts on the nutrition value.
(3) From (1) and (2) provision of a quantitative food product classification base to apply either separate F & P levels or quantitatively recoupled F & P levels expressed by the nutrition value-related (superscript N) Formulation and Processing Food Index FPFI^N as classification parameters.
(4) Use of the classification base according to (3) for improved correlative comparison with data on obesity and associated health risks (Food Impact Correlation).
(5) Differentiating conclusions on F & P or FPFI^N influences with regard to determined food impact correlation results according to (4).
(6) Indication of the possibility to extend considerations for processed foods concerning other product properties in addition to the nutritional value (e.g.: satiation kinetics and palatability in the NOVA context, but as well sustainability, safety, convenience and affordability; see Fig. 1 and Table 5) and their handling according to the IF&PC scheme.
(7) Further development of the classification base for processed foods at the point of Purchase (POP) in accordance with (6) for appropriate quantitative use in further refined correlation analyses according to (4)
(8) Iterative refinement of the classification and correlation procedures according to steps (1)-(7), applying appropriately extended classification parameters for levels of formulation (NRF*x.y.z) and processing (ΔNRF*x.y.z) which account for quantitative digestive and metabolic response characteristics, thereby refining food impact correlations with health promotion/health risk data to ultimately derive evidence-based causal functional relationships.

Transferability of the IF&PC Approach

As introduced and discussed throughout this report, the core of the IUFoST Formulation and Processing Classification approach (IF&PC) is the separation and quantification of formulation and processing impacts on the exemplarily selected Nutrition Value as the most relevant food property parameter underlaid to the NOVA classification system. The extended Nutrition Rich Food Index NRF**x.y.z* and its difference between food product states before and after a processing treatment (ΔNRF**x.y.z*) were successfully pre-validated as suitable Classification Parameters (CP) for quantitative formulation and processing impacts. This sub-chapter intends to demonstrate the prospective generalizability of this approach with respect to other food product characteristics than the nutrition value. As addressed in the "Key definition 1" chapter further main food product properties of consumer relevance are: (a) safety, (b) sustainability, (c) palatability, (d)

Table 5 | Suggested classification parameters for major (1–6) and specific (7,8) consumer-relevant food product properties

No.	Product property (PP)	Formulation (F) - CPs	Processing (P) - ΔCPs	F&P coupling
1	Nutrition Value	E.g. NRF*$x.y.z$	ΔNRF*$x.y.z$	$FPFI^{N}$
2	Sustainability	E.g. Global warming potential (GWP)	ΔGWP (global warming potential) difference	$FPFI^{SU}$
3	Palatability	E.g. Sensory Score (SS) Energy consumption to reach satiation (EC-Sat) Volume consumption to reach satiation (VC-Sat)	ΔSS ΔEC-Sat ΔVC-Sat	$FPFI^{SS}$ $FPFI^{EC\text{-}Sat}$ $FPFI^{VC\text{-}Sat}$
4	Safety	E.g. Colony forming unit (CFU) count	ΔCFU	$FPFI^{CFU}$
5	Convenience	E.g. Convenience score (CS)	ΔCS	$FPFI^{CS}$
6	Affordability	E.g. Energy consumption/$ or NRF$x.y$/$; NRF*$x.y.z$/$	ΔEC$ ΔNRF/$; ΔNRF*/$	$FPFI^{EC\$}$ $FPFI^{NRF\$}$ $FPFI^{NRF*\$}$
7	Digestibility: e.g. for proteins	E.g. PDCAAS DIAAS	ΔPDCAAS ΔDIAAS	$FPFI^{PDCAAS}$ $FPFI^{DIAAS}$
8	INFOGEST (IG) parameters $P_1 \ldots P_N$	E.g. IG-Pi	ΔIG-Pi	$FPFI^{IGPi}$

PDCAAS = protein digestibility corrected amino acid score, DIAAS = ratio of digestible amino acid content in the food (mg/g of protein) to the same amino acid in a reference pattern taken from age-specific amino acid requirements; INFOGEST = in vitro simulation of gastrointestinal food digestion.

No. 1 in Table 5 represents the case treated in detail within this report. In some of the product properties like 1 (Nutrition Value), 3 (Palatability), 4 (Safety), 5 (Convenience), and 7 (Digestibility), the processing is known to allow for improvements. However, improvement in one of these may cause trade-offs for another one.

For No. 2 (Sustainability) processing will, in general, add an additional negative load. However different ways of processing can be differentiated, and the least burdensome process can be identified and selected.

For No. 6 (affordability) processing costs are added; however, the resulting product could be cheaper due to concentration effects impacting positively e.g. on transport costs and nutritional effects (e.g. satiation efficiency, nutritional energy supply efficiency) the latter may be of specific relevance in developing countries but also in domains like sports nutrition[53].

No. 7 (Digestibility) is seen as a key part of a promising development which is expected to lead to more evidence-based correlations and finally to functional relationship insights between the quality of food products at the point of purchase (POP) and digestion as well as metabolic response characteristics, which in turn will provide a quantitative base for next step correlations and functional dependency derivations concerning obesity and related health risk aspects.

Thus, the IF&PC scheme suggested by this report is expected to have the potential to pave the way for an appropriate prospective consideration of processing impacts on food product quality in a holistic manner. For such a holistic approach, which will enable addressing a number of quality criteria Qi for formulated and processed food products, the obvious question is whether an associated multi-parameter classification can still be communicated to the consumer. In this regard, it will generally be possible to use a coding system (e.g. QR) to call up the classification results for various quality criteria Q1 to Qn of a product and to clearly visualize related scores. The weighting of the various Qi should be left to the discretion of the product developers and ultimately the consumers.

convenience and (e) affordability. To apply the IF&PC scheme representatively, the property-related classification parameters (CPs) have to be selected first. Table 5 suggests CPs for the named food product properties.

Digestibility (f) and (g) metabolic response aspects could also be approached e.g. in case of motivation for a further refinement and causalization steps to be addressed to NOVA's correlation approach between nutritional food charactetristics and related obestity and health risk outcomes.

For all of the main food properties named before (a)–(g) one can explore differentiated property-specific formulation (F) and processing (P) classification parameters, derive a two-parameter (F&P) classification and consolidate to a one-parameter ($FPFI^{x}$) classification.

Such a holistic approach creates a quantifiable basis for the realistic development of food products, which usually also has to take into account other product properties in addition to the nutritional value.

For both scenarios, the NOVA System refinement and the more holistic consideration of several essential food product properties, there are demanding future R&D and industrial application requirements which relate to the systematic acquisition of data (classification parameters CP, like e.g NRF$x.y.z$ and ΔNRF$x.y$ applied for the nutrition value) for food product formulations before and after execution of processing steps.

Such data will support research on the IF&PC scheme application in a wider food product framework to validate and refine the scheme. Related investigations should include all suggested food properties of major relevance.

In order to successfully manage accessing and orchestrating the required interdisciplinary expertise the IUFoST task force highly recommends to the communities of food scientists, food engineers, nutrition scientists and related professionals as they are, e.g., represented by IUFoST and IUNS to join forces and encourage concerted international R&D actions.

From our perspective as the IUFoST Task Force on Processing for Nutrition, Diet and Health, we hope to have efficiently nucleated an ongoing development process that provides good prospects for successful collaboration between food scientists, food engineers, and nutrition scientists in jointly developing future classifications of processed foods and, building on this, establishing evidence-based functional relationships between the properties of processed foods and their impact on important consequences for consumers and the environment.

Concluded R&D requirements in food science/engineering and nutrition

(a) Systematic studies should consider interactions between food components/ingredients and processes and quantify NRF and ΔNRF values systematically following the IF&PC scheme approach. Such should also be carried out for serially arranged processing steps. Food databases should be complemented by such data sets for processed foods/food components considering different processes and processing intensities without mixing such up with variations in formulation.

(b) The IF&PC scheme should be systematically checked and validated based on various formulation and processing scenarios and modifications/improvements be implemented.

(c) Complementary studies should look at interactions between additives and processes and also study matrix effects impacting nutrient release and digestion kinetics. A comprehensive literature (including work from the Codex Alimantarius) already exists on several ingredients and additives, and for most of these the totality of evidence does not support harmful health effects. Such additives should not be part of a novel classification system. By contrast, the evidence used to develop current authoritative guidelines supports recommendations on nutrients and food components of public health concern, which varies by country, but can include the adequacy of certain nutrients (e.g. fibre or calcium) as well as nutrients and food components to limit (e.g. added sugars, *trans* fatty acids, sodium) and these criteria should be included.

(d) Harmful processes and additives should be identified. A revised definition of "Formulation- or Process-Induced Health Risk Foods" (FI-HRF; PI-HRF) needs to start with the identification of the harmfulness of processing treatments and/or single, specific ingredients using reliable health biomarkers, and by conducting dose–response relations to identify thresholds.

(e) An international balanced panel of experts from food science, food process engineering, human nutrition, and medicine should be gathered to draft the future development of the IF&PC scheme and its possible application in NOVA refinement actions. Subsequently, there should be a hearing phase to receive suggestions for improvements. The panel should also produce a research plan for studies that need to have their usefulness confirmed before being launched. Such a research plan should involve animal studies, mechanistic human studies, observational studies, and randomized controlled trials. Clear criteria for positive study outcomes should be defined, as well as the totality of evidence required to endorse the further launch of a refined classification system.

(f) Close R&D collaborations between food science, food engineering, biological chemistry, clinical nutrition, public health and toxicology researchers and those involved in regulatory and quality sciences should be encouraged and setup addressing the before-mentioned actions. Such collaborations should also include industrial partners (food producers, food processing developers, and equipment manufacturers).

Methods

Nutrition value

For Nutrition Value quantification the Nutrition Rich Food Index (NRF*x.y*) was applied. The Nutrient Rich Food (NRF) Index is a nutrient profiling method that scores foods based on their nutrient content per 100 kcal (418.4 kJ). It considers both beneficial nutrients (protein, fibre, vitamins A, C, E, B12, calcium, iron, zinc, potassium, and others) and nutrients to limit (saturated fat, added sugar, and sodium). The most common version, NRF9.3, includes 9 beneficial nutrients and 3 nutrients to limit. The formula calculates the percentage of daily recommended values for each nutrient, capping beneficial nutrients at 100% to avoid overvaluation of fortified foods. The final score is determined by subtracting the sum of limiting nutrient percentages from the sum of beneficial nutrient percentages. Higher scores indicate more nutritious foods. This index is used in nutrition profiling and policy-making to evaluate and compare the nutritional quality of different foods and diets.

The NRF Index was initially developed by A. Drewnowski and colleagues. Key literature sources include: Drewnowski A. (2010) "The Nutrient Rich Foods Index helps to identify healthy, affordable foods" published in The American Journal of Clinical Nutrition, introducing the NRF9.3 algorithm and validating it against the Healthy Eating Index[1] and Drewnowski A. (2009); "Defining nutrient density: development and validation of the nutrient rich foods index" in the Journal of American Colledge of Nutrition[20]. The NRF9.3 calculations typically use nutrient composition data from national food composition databases, such as (i) USDA's National Nutrient Database for Standard Reference, (ii) National food composition tables specific to different countries and (iii) Commercial nutrition databases. Foods are generally analysed in their retail/purchased form, though some studies specify different preparation states (raw, cooked, prepared). Hence the NRF describes the nutritional value of a food formulation. The state of the food should be clearly defined since cooking and preparation can affect nutrient content significantly. The reference amounts for daily values typically come from national dietary guidelines like the US FDA's Daily Values or similar national standards. The description of the influence of processing methods on the nutritional value of processed food products using the NRFx.y is initially limited to changes in composition due to the enrichment or loss of qualifying nutrients (NR term; see Formula 1) and disqualifying nutrients (LIM term; see Formula 1). However, the NRFx.y definition allows for extensions to include additional terms that take into account other formulation and processing influences that contribute to the nutritional value (see chapter "Extension of the IF & PC application frame". As an example, in further detail, the Supplementary Information addresses the group of anti-nutrients using exemplarily phytic acid, which can be present in higher concentrations in plant-based food raw materials. Phytic acid can form complexes with nutritionally important minerals (e.g., Fe, Zn) and with proteins, leading to a reduction in the nutritional value due to partial to complete loss of bioavailability of such nutrients. Processing (thermal, mechanical, and enzymatic) can inactivate anti-nutrients and thus contribute to a significant improvement in the nutritional value of correspondingly processed foods[36]. Consequently, if an anti-nutrient term (ANz) is introduced into the extended NRF* definition with a negative sign, the representation of a modified NRF*x.y.z allows the formulation-based influence of anti-nutrients (phytic acid/phytate in the example) and the degree of influence through inactivating processes to be captured by ΔNRF*x.y.z. Accordingly, the NRF can be expanded to include additional terms that allow for further aspects of the nutritional value (e.g., protein digestibility, see Table 5) to be considered.

Processing impact on Nutrition value

As developed within the work for this report in the chapter "Differentiation of Formulation and Processing in Food Classification by definition and quantification", the processing impact on the nutritional value is determined by calculating ΔNRFx.y, which is the difference between the NRFx.y values after and before processing. Thus ΔNRFx.y is a quantitative measure of how processing affects a food's nutritional value defined and quantified based on the NRFx.y by comparing its nutrient profile before and after the processing treatment. The resulting value serves as a classification parameter for the degree of processing's impact on the nutritional quality. Similar to how energy and mass balances measure the quantitative change across process boundaries (input vs. output), the ΔNRFx.y thus results from a "nutritional value balance".

Formulation and processing food index $FPFI^N$

The coupled impact of formulation level (F) expressed by NRF9.3 and processing level (P) expressed by ΔNRFx.y can be quantitatively expressed by the "Food Processing and Formulation Index" $FPFI^N$ introduced in the work reported here, the superscript N indicating the nutrition value as the considered food property being classified. Thus, $FPFI^N$ values represent quantitative Nutrition Value classes, which are demonstrated in a Classification Matrix Diagram (CMD) introduced here with Iso-$FPFI^N$ lines (lines of constant $FPFI^N$). The Classification Matrix Diagram (CMD, see figs. 6 and 7) is suggested for the graphical representation of (i) the NRFx.y as quantitative nutrition value-related "formulation level" classification parameter (CP1) dependency of (ii) **Δ**NRF9.3, the quantitative nutrition value-related "processing level" classification parameter (CP2).

Data availability

(1) Data is provided within the manuscript or supplementary information files. (2) Data is also taken from U.S. Department of Agriculture, Agricultural Research Service (2020). Food and Nutrient Database for Dietary Studies 2019–2020. Food Surveys Research Group Home Page[37]: (http://www.ars.usda.gov/nea/bhnrc/fsrg).

Received: 27 January 2025; Accepted: 19 February 2025;
Published online: 23 April 2025

References

1. Drewnowski, A. The nutrient rich foods index helps to identify healthy, affordable foods. *Am. J. Clin. Nutr.* **91**, 1095S–1101SS (2010).
2. Drewnowski, A. Concept of a nutritious food: toward a nutrient density score. *Am. J. Clin. Nutr.* **82**, 721–732 (2005).
3. Azaïs-Braesco, V., Goffi, C. & Labouze, E. Nutrient profiling: comparison and critical analysis of existing systems. *Public Health Nutr.* **9**, 1–10 (2006).
4. EFSA Panel on Nutrition, Novel Foods and Food Allergens (NDA), et al. *Scientific Advice Related to Nutrient Profiling for the Development of Harmonised Mandatory Front-of-pack Nutrition Labelling and the*

Setting of Nutrient Profiles for Restricting Nutrition and Health Claims on Foods (Wiley-VCH Verlag GmbH & Co. KgaA, 2022).
5. Eichelsdoerfer, P. et al. Testing Nutrient Rich Foods (NRF) Indices against US national food prices and consumer perceptions of the foods' economic and nutritional value. *J. Am. Diet. Assoc.* **109**, A49 (2009).
6. Monteiro, C. A. Nutrition and health. The issue is not food, nor nutrients, so much as processing. *Public Health Nutr.* **12**, 729–731 (2009).
7. Monteiro, C. A. et al. The UN Decade of Nutrition, the NOVA food classification and the trouble with ultra-processing. *Public Health Nutr.* **21**, 5–17 (2017).
8. Monteiro, C. A. et al. Ultra-processed foods: what they are and how to identify them. *Public Health Nutr.* **22**, 936–941 (2019).
9. Sadler, Ch. R. et al. Processed food classification: conceptualisation and challenges. *Trends Food Sci. Technol.* **112**, 149–162 (2021).
10. Monteiro, C.A., Cannon, G., Lawrence, M., Costa Louzada, M.L. & Pereira Machado, P. Ultra-processed foods, diet quality, and health using the NOVA classification system. Rome, FAO (2019).
11. Astrup, A. & Monteiro, C. A. Does the concept of "ultra-processed foods" help inform dietary guidelines, beyond conventional classification systems? *Am. J. Clin. Nutr.* **116**, 1482–1488 (2022).
12. Drewnowski, A., Gupta, S. & Darmon, N. An overlap between "ultraprocessed" foods and the preexisting nutrient rich foods index? *Nutr. Today* **55**, 75–81 (2020).
13. Hess, J. M. et al. Dietary guidelines meet NOVA: developing a menu for a healthy dietary pattern using ultra-processed foods. *J. Nutr.* **153**, 2472–2481 (2023).
14. Braesco, V. et al. Ultra-processed foods: how functional is the NOVA system? *Eur. J. Clin. Nutr.* **76**, 1245–1253 (2022).
15. Gupta, S., Hawk, T., Aggarwal, A. & Drewnowski, A. Characterizing ultra-processed foods by energy density, nutrient density, and cost. *Front. Nutr.* **6**, 70 (2019).
16. Trumbo, P. R. et al. Toward a science-based classification of processed foods to support meaningful research and effective health policies. *Front. Nutr.* **11**, 1389601 (2024).
17. Gibney, M. J., Forde, C. G., Mullally, D. & Gibney, E. R. Ultra-processed foods in human health: a critical appraisal. *Am. J. Clin. Nutr.* **106**, 717–724 (2017).
18. Gibney, M. J. & Forde, C. G. Nutrition research challenges for processed food and health. *Nat. Food* **3**, 104–109 (2022).
19. Knorr, D. et al. *European Technology Platform on Food for Life: Strategic Research Agenda 2007–2020;* http://cordis.europa.eu/article/id/28361-food-etp-unveils-strategic-research-agenda (2007).
20. Drewnowski, A. Defining nutrient density: development and validation of the nutrient rich foods index. *J. Am. Coll. Nutr.* **28**, 421S–426S (2009). 2009 Aug.
21. Drewnowski, A. A novel Nutrient Rich Food (NRFa11.3) score uses flavonoids and carotenoids to identify antioxidant-rich spices, herbs, vegetables, and fruit. *Front. Nutr.* **11**, 1386328 (2024).
22. Wu, D.-T. et al. A comprehensive review of pea (*Pisum sativum* L.): chemical composition, processing, health benefits, and food applications. *Foods* **2023**, 2527 (2023).
23. Food Surveys Research Group. USDA, Food and Nutrient Database for Dietary Studies (FNDDS). Food Surveys Research Group, Beltsville Human Nutrition Research Center. *Dataset*. http://hdl.handle.net/10113/AA5879 (2017).
24. Monteiro, C. A. et al. Ultra-processing. An odd 'appraisal'. *Public Health Nutr.* **21**, 497–501 (2018).
25. Monteiro, C. A., Levy, R. B., Claro, R. M., De Castro, I. R. & Cannon, G. A new classification of foods based on the extent and purpose of their processing. *Cad. Saúde Pública* **26**, 2039–2049 (2010).
26. Monteiro, C. A., Levy, R. B., Claro, R. M., de Castro, I. R. R. & Cannon, G. Increasing consumption of ultra-processed foods and likely impact on human health: evidence from Brazil. *Public Health Nutr.* **14**, 5–13 (2011).
27. Monteiro, C. A., Moubarac, J.-C., Cannon, G., Ng, S. W. & Popkin, B. Ultra-processed products are becoming dominant in the global food system. *Obes. Rev.* **14**, 21–28 (2013).
28. Steele, E. M. et al. Ultra-processed foods and added sugars in the US diet: evidence from a nationally representative cross-sectional study. *BMJ Open* **6**, Article e009892 (2016).
29. da Costa Louzada, M. L. et al. Validating the usage of household food acquisition surveys to assess the consumption of ultra-processed foods: Evidence from Brazil. *Food Policy* **72**, 112–120 (2017).
30. Mendoza-Velázquez, A., Lara-Arévalo, J., Siqueira, K. B., Guzmán-Rodríguez, M. & Drewnowski, A. Affordable nutrient density in Brazil: nutrient profiling in relation to food cost and NOVA category assignments. *Nutrients* **14**, 4256 (2022). 2022.
31. Drewnowski, A., Detzel, P. & Klassen-Wigger, P. Perspective: achieving sustainable healthy diets through formulation and processing of foods. *Curr. Dev. Nutr.* **6**, https://doi.org/10.1093/cdn/nzac089 (2022).
32. Drewnowski, A. Perspective: identifying ultra-processed plant-based milk alternatives in the USDA branded food products database. *Adv. Nutr.* **12**, 2068–2075 (2021).
33. Drewnowski, A., Smith, J. & Fulgoni, V. L. III The new hybrid nutrient density score NRFh 4: 3: 3 tested in relation to affordable nutrient density and healthy eating index 2015: analyses of NHANES data 2013–16. *Nutrients* **13**, 1734 (2021).
34. Aggarwal, A., Rehm, C. D., Monsivais, P. & Drewnowski, A. Importance of taste, nutrition, cost and convenience in relation to diet quality: Evidence of nutrition resilience among US adults using National Health and Nutrition. *Prev. Med.* **90**, 184–192 (2016).
35. Fern, E. B., Watzke, H., Barclay, D. V., Roulin, A. & Drewnowski, A. The nutrient balance concept: a new quality metric for composite meals and diets. *PLoS ONE* **10**, e0130491 (2015).
36. Patterson, C. A., Curran, J. & Der, T. Effect of processing on antinutrient compounds in pulses. *Cereal Chem.* **94**, (2017)
37. U.S. Department of Agriculture, Agricultural Research Service. *Food and Nutrient Database for Dietary Studies 2019–2020*. Food Surveys Research Group Home Page http://www.ars.usda.gov/nea/bhnrc/fsrg (2020).
38. González-Castell, D, González-Cossío, T, Barquera, S & Rivera, J. A Alimentos industrializados en la dieta de los preescolares mexicanos [Contribution of processed foods to the energy, macronutrient and fiber intakes of Mexican children aged 1 to 4 years]. *Salud Publica Mex.* **49**, 345–356 (2007). (in Spanish).
39. Slimani, N. et al. Contribution of highly industrially processed foods to the nutrient intakes and patterns of middle-aged populations in the European Prospective Investigation into Cancer and Nutrition study. *Eur. J. Clin. Nutr.* **63**, S206–S225 (2009).
40. Chaj'es, V. et al. Ecological-level associations between highly processed food intakes and plasma phospholipid elaidic acid concentrations: results from a cross-sectional study within the European Prospective Investigation into Cancer and Nutrition (EPIC). *Nutr. Cancer* **63**, 1235–1250 (2011).
41. Moubarac, J.-C., Batal, M., Louzada, M. L., Martinez Steele, E. & Monteiro, C. A. Consumption of ultra-processed foods predicts diet quality in Canada. *Appetite* **108**, 512–520 (2017).
42. Schnabel, L. et al. Association between ultra-processed food consumption and functional gastrointestinal disorders: results from the French NutriNet-Sant´e cohort. *Am. J. Gastroenterol.* **113**, 1217–1228 (2018).
43. Asfaw, A. Does consumption of processed foods explain disparities in the body weight of individuals? The case of Guatemala. *Health Econ.* **20**, 184–195 (2011).
44. Moubarac, J.-C., Parra, D. C., Cannon, G. & Monteiro, C. A. Food classification systems based on food processing: significance and implications for policies and actions: a systematic literature review and assessment. *Curr. Obes. Rep.* **3**, 256–272 (2014).

45. Eicher-Miller, H. A., Fulgoni, V. L. I. & Keast, D. R. Contributions of processed foods to dietary intake in the US from 2003–2008: a report of the Food and Nutrition Science Solutions Joint Task Force of the Academy of Nutrition and Dietetics, American Society for Nutrition, Institute of Food Technologists, and International Food Information Council. *J. Nutr.* **142**, 2065S–2072S (2012).
46. Eicher-Miller, H. A., Fulgoni, V. L. I. & Keast, D. R. Energy and nutrient intakes from processed foods differ by sex, income status, and race/ethnicity of US adults. *J. Acad. Nutr. Diet.* **115**, 907–918.e6 (2015).
47. da Costa Louzada, M. L. et al. Consumption of ultra-processed foods and obesity in Brazilian adolescents and adults. *Prev. Med.* **81**, 9–15 (2015).
48. Poti, J. M., Mendez, M. A., Ng, S. W. & Popkin, B. M. Is the degree of food processing and convenience linked with the nutritional quality of foods purchased by US households? *Am. J. Clin. Nutr.* **101**, 1251–1262 (2015).
49. Fardet, A. Characterization of the degree of food processing in relation with its health potential and effects. In *Advances in Food and Nutrition Research* Vol. 85 (ed. Toldrá, F.) 79–129 (Elsevier Inc., 2018).
50. Siga. Siga, une d́ emarche scientifique pour aḿ eliorer et promouvoir la qualit ́e des aliments [Siga, a scientific approach to improve and promote the quality of food] (Siga, 2019).
51. Fulgoni, V. L. III, Keast, D. R. & Drewnowski, A. Development and validation of the nutrient-rich foods index: a tool to measure nutritional quality of foods. *J. Nutr.***23**, 2009 (2009).
52. Ridoutt, B An alternative nutrient rich food index (NRF-ai) incorporating prevalence of inadequate and excessive nutrient intake. *Foods* **10**, 3156 (2021).
53. Madlala, S. S, Hill, J, Kunneke, E & Faber, M Nutrient density and cost of commonly consumed foods: a South African perspective. *J. Nutr. Sci.* **12e10**, 1–13 (2023).
54. Windhab E. J. *Structure-based Quality and Health Related Function Tailoring in Food Systems—A Process Engineering Approach*. ETH-M.Sc./Ph.D. lecture course in Food Process Engineering http://www.researchgate.net/publication/242465838 (2008).
55. Fernández-Quintela, A., Macarulla, M. T., Del Barrio, A. S. & Martínez, J. A. Composition and functional properties of protein isolates obtained from commercial legumes grown in northern Spain. *Plant Foods Hum. Nutr.* **51**, 331–342 (1997).

Acknowledgements
The authors thank A. Drewnowski for advice on the Nutrition Rich Food Index application. L. Neufeld, B. Burlingame for nutrition-related discussion contributions, and S. Saguy and Y. Roos for discussion and contributions in the early stage of the task force work. Further thanks go to A.-M. Hermansson, R. Clemens, P.G. Rao and L. Ke who acted as critical readers. Last but not least, we thank A. Wirakartakusumah, S. Godefroy and J. Meech for efficient IUFoST support and the Advisory Board to the Task Force with S. Saguy, L. Ahrné, J. von Braun, A. Drewnowski, M. Gibney, P. Rao and S. Sastry for their readiness to give initial specific helpful advice. The authors also thank Ch. Slatter for the allowance and rights to use Fig. 5 of this report. The views expressed in this report are those of the authors and not necessarily those of the US Government or the author's agency.

Author contributions
L.A. contributed to project ideation and conceptualization, investigation, discussion, supervision, validation, response to reviewers and writing. H.C. contributed to project ideation and conceptualization, investigation, discussion, supervision, validation, response to reviewers and writing. J.H. contributed to project ideation and conceptualization, investigation, discussion, supervision, validation, response to reviewers and writing. H-S.K. contributed to project ideation and conceptualization, investigation, discussion, supervision, validation, response to reviewers and writing. B.S. contributed to project ideation and conceptualization, investigation, discussion, supervision, validation, response to reviewers and writing. E.J.W. contributed to data analysis, data curation, project ideation and conceptualization, project administration, method development, supervision, validation, visualization, response to reviewers, and writing and chaired the IUFoST task force.

Competing interests
H.C. serves as an Associate Editor of *npj Science of Food* but had no role in the peer-review or decision to publish this manuscript. The remaining authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41538-025-00395-x.

Correspondence and requests for materials should be addressed to Erich J. Windhab.