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Beyond ultra-processed: considering the future role of food processing in human health

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Food-based dietary guidelines have been the basis of public health recommendations for over half a century, but more recently, there has been a trend to classify the health properties of food not by its nutrient composition, but by the degree to which it has been processed. This concept has been supported by many association studies, narrative reviews and the findings from one randomised controlled feeding trial, which demonstrated the sustained effect of ultra-processed diets on increasing both energy intake and body weight. This has led to widespread speculation as to specific features of ultra-processed foods that promote increased energy intakes. Rising interest in the ultra-processed topic has led to proposals to include guidance and restrictions on the consumption of processed foods in national dietary guidelines, with some countries encouraging consumers to avoid highly processed foods completely, and only choose minimally processed foods. However, there remains a lack of consensus on the role of processed foods in human health when faced with the challenges of securing the food supply for a growing global population, that is, healthy, affordable and sustainable. There has also been criticism of the subjective nature of definitions used to differentiate foods by their degree of processing, and there is currently a lack of empirical data to support a clear mechanism by which highly processed foods promote greater energy intakes. Recommendations to avoid all highly processed foods are potentially harmful if they remove affordable sources of nutrients and will be impractical for most when an estimated two-thirds of current energy purchased are from processed or ultra-processed foods. The current review highlights some considerations when interpreting the dietary association studies that link processed food intake to health and offers a critique on some of the mechanisms proposed to explain the link between ultra-processed food and poor health. Recent research suggests a combination of higher energy density and faster meal eating rates are likely to influence meal size and energy intakes from processed foods and offers new perspectives on how to manage this in the future. In going beyond the ultra-processed debate, the aim is to summarise some important considerations when interpreting existing data and identify the important gaps for future research on the role of processed food in health.

Ultra-processed: Energy intake: Observational data: Eating rate: Energy density

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Abbreviations: RCT, randomised controlled trials; UPF, ultra-processed foods..
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What are (ultra)processed foods?

There is widespread agreement that we need to change the way we produce the foods we consume, with rising levels of diet-related chronic disease matched by global concerns on the environmental impact of food production and distribution. Food-based dietary recommendations are supported by scientific evidence that underpins population guidance on healthy eating, with the goal of minimising diet-related chronic disease and enhancing nutritional well-being across the lifespan. These guidelines are informed by the highest quality scientific research from longitudinal observation studies and randomised controlled trials (RCT) within target and general populations. In recent years, dietary recommendation has moved away from nutrient-specific guidance (e.g. increase calcium and vitamin D for bone health), to emphasise the contribution of whole foods (i.e. milk) and food groups (i.e. dairy) in promoting nutrient adequacy. In 2009, a group in Brazil proposed the 'NOVA' approach to classify foods, not by their nutrient content, but by the degree to which they have been processed[1]. This approach proposes that it is not the nutrients in a food that predict its health properties, but the degree of processing that is most important for health. The NOVA approach advises the complete avoidance of highly processed foods to maximise health[2], and although quite subjective, the approach has a simplicity that is appealing when compared to more complex systems to code processed food or detailed dietary guidance based on nutrients or food groups.

There are currently at least six different systems that are used to classify foods by their degree of processing including the European Prospective Investigation into Cancer[3], the International Food Information Council[4], the Siga classification[5], the University of North Carolina[6], NOVA and more recently the Food Compass system[7]. The NOVA system has evolved considerably since its initial introduction, initially focusing on number of ingredients and processes and more recently evolving to include the 'purpose of processing' as a central component of the definition[8]. There is little cohesion between these different systems of processing classification, and this becomes apparent when the same dietary data set is compared using different processing classification approaches, resulting in wide variation in the reported associations between processed food consumption and health. When data from the PREDIMED trial were classified using four of these different processing classifications (NOVA, the European Prospective Investigation into Cancer, the International Food Information Council, the University of North Carolina), the resulting associations with health varied considerably across systems, with most significant associations either attenuated or lost completely[9]. The NOVA scheme is the simplest and by far the most widely used approach to classify foods and diets by their degree of processing, but it's worth noting that there is a lack of consensus on its formulation and its application in dietary epidemiology[10–12]. The aim of the current review is to provide a critique of available evidence and mechanisms and to highlight some important considerations for future research priorities on the topic of food processing and health.

The purpose of food processing and the objectivity of a definition

The NOVA system classifies foods based on (i) the extent and (ii) purpose of their processing into four categories from minimally processed (1), processed culinary ingredients (fats/oils, salt) (2), processed foods (3) and ultra-processed foods (UPF) (4)[13]. Minimally processed foods are the original whole food with no additives which undergo only mild or minimal processing and include fresh meats, fruits, vegetables and dairy. Processed culinary ingredients include salt, sugar and refined oils and other ingredients that are derived from the original whole food. When processed culinary ingredients are added to minimally processed foods, they join the processed food category, which also includes salting, canning, fermenting, freezing and prepared food that has undergone several processing steps. The UPF category is distinct from other processed foods and describes foods as '*industrial formulations that are made entirely from food derivatives, chemical substances and sequence of processes, that bears little resemblance to the original food material*'[13]. In addition to degree of processing and formulation described earlier, the definition extends further to include the motivation behind specific formulations, such as '*the use of additives whose function is to make the final product palatable and more appealing*'[1]. The NOVA system overlaps with many existing nutrient indices[14], but is unique among classification approaches in that NOVA 4 (ultra-processed) category is the least discriminating, offering the broadest grouping of packaged foods available for consumption in the modern food environment. As such, when correlations are made with health markers or diet-related chronic disease, this category of foods is more likely to yield significant associations between processed food consumption and negative health outcomes. The popularity of the NOVA system has grown slowly since its inception, originally only used by small groups of researchers in specific regions[15], but has since grown to become the most popular and widely used classification in the published literature and is increasingly referred to in FAO and WHO recommendations[1].

This concept that the 'purpose of food processing' should be included as part of an objective definition of processed food is a unique element of the NOVA classification scheme, when compared to the other approaches. Here the NOVA definition goes beyond a product's composition or even degree of processing to include the motivation or *reason* behind the processing or formulation. These reasons have been listed in the definition as processing materials '*to drive profitability, affordability, (hyper)palatability, convenience and ubiquity, where processed products are available everywhere, are affordable, and are widely marketed*'[16]. The ultra-processed definition highlights further links with purpose, where

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ingredients that are added to '*mimic the sensorial quality of unprocessed or minimally processed foods and their culinary preparations or to disguise undesirable qualities of the final product*'[16]. Here the emphasis is not on the specific chemical or nutrient properties of the ingredient *per se*, but rather the intention behind its addition, suggesting the motivation for why a food is formulated this way is part of what qualifies it as (ultra)processed, and thus linked to a negative health impact. This is a clear departure from traditional nutrient-based dietary guidelines where the NOVA scheme describes 'purpose' of processing and formulation as part of the problem, and where product elements such as profitability, convenience, palatability or affordability are seen to play a role in the health or nutrient quality of the product[17].

Food processing is a broad term that encompasses many different unit operations that are applied for a variety of different reasons, and although primarily used to increase the safety and digestibility of raw materials, they cannot all be described or defined as a single formulation or 'process'[18]. These approaches are applied to enhance sensory properties, ensure safety, extend shelf-life and improve nutrient (bio)availability among other reasons. Including 'purpose of processing' in the NOVA definition opens the classification to subjective interpretations of the intended purpose, increasing the risk of a biased interpretation and misclassification of processes and related health outcomes. This creates a separate, but related, debate on the potential to conflate the healthfulness of a food with an individual's own ideological bias against the modern food production system, or preconceptions towards the economic success of large food producers. Importantly, to date, there is no evidence that foods that are unprofitable, unpalatable, expensive or inconvenient to eat are necessarily better for your health. Moreover, producing foods that are unappealing and more expensive may reduce their intake in the short-term, but is unlikely to be a popular approach among consumers or food producers, and hardly seems a strong basis for public health strategies that aim to combat diet-related chronic disease[19]. It is unlikely that company size, profitability or the 'purpose' of processing will inform dietary guidance in the future, and recommendations will continue to be firmly grounded in the evidence related to an objective appraisal of a foods nutritive value, and its potential to support healthy dietary patterns.

A critique of the observational evidence on the impact of processed food on health

Challenges with inferences made from observational studies using the NOVA classification

The NOVA classification has been widely applied to observational dietary epidemiological studies to establish links between the consumption of processed foods and a wide range of health outcomes. This includes cardiometabolic disease, obesity and mortality (see[20] for a meta-analysis of observational studies). Insights from observational trials are limited by the nature of the dietary database, and the available details on food composition and processing steps for each item. It is widely recognised that observational comparisons cannot establish causality[21], but rather these approaches are often used to generate research hypotheses that should later be tested in randomised controlled diet trials. The exponential growth of publications linking processed food consumption to health research is based largely on repetitive observational studies that have shown similar associations between NOVA 4 UPF intake and health outcomes using dietary data sets from around the world[22].

Within dietary association studies, it is important to control for known covariates that may bias a comparison or lead to an unfair attribution of influence to factors assumed to drive an observed association with health outcomes[21]. Few studies to date have accounted for many of the known covariates that can influence the strength of relationships reported when comparing the processed food intake and health, with only a handful controlling for diet quality, energy density or other known lifestyle covariates. In addition to diet quality and energy density, other confounders with established links to obesity and poor health are often overlooked including physical (in)activity, smoking, alcohol consumption, stress, depression, poor sleep quality and duration, lower socio-economic status. When known dietary covariates are not controlled, it makes it unclear whether the impact of food processing has a distinct impact on health beyond established links between low diet quality and an increased risk of diet-related chronic disease. These findings are therefore susceptible to confounding where exposure to higher processed food intakes is associated with poor health outcomes without eliminating other known and measured factors[23].

Recent studies have begun to adjust for diet quality (i.e. correcting for health eating index) in comparisons linking processed food intake to health outcomes and in some cases the link with processed food intake and chronic conditions is maintained[24,25]. However, other studies have demonstrated that the relationship between UPF intake and poor health is mediated by diet quality[26], suggesting no additional unique contribution of processing on health when poor diet quality is controlled. Future research will be needed to establish the strength of the relationship between UPF intake and health when all known covariates have been accounted for in the analysis. There is now a need to supplement the outcomes of these observational data comparisons, with controlled feeding studies to establish whether the relationship between UPF consumption and health is independent of its relationship with poor diet quality.

Coder agreement on ultra-processed categorisation of dietary data sets

The NOVA definition of processing has continued to evolve since originally introduced to clarify what is regarded as ultra-processed, and many have been critical of the vague nature of the definitions which can be easily misinterpreted[8,12]. Currently, the NOVA definition

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includes elements of processing, formulation and processing 'purpose', and in recent years has further incorporated subjective terms such as 'home-made' or 'natural'. Several studies have shown large discrepancies in agreement when foods are coded using different classification schemes. For example, when the 100 most commonly consumed foods were coded, there were large discrepancies between NOVA, the University of North Carolina and the International Food Information Council, and poor agreement on which classification system is best to identify foods with high nutrient quality[6]. This creates issues when nutrition experts can easily misinterpret the same definitions and classify foods in different ways. Furthermore, the shifting nature of the UPF definition has led to confusion and ambiguity, which questions the stability and inter-rater reliability of the classifications used in the many observational epidemiological studies that seek to link UPF intake to health. A recent French study highlighted this and asked over 300 nutrition professionals to classify 231 different food items into their NOVA categories and found that 98 % of foods were placed in different processing categories by all assessors and there was agreement for only four of the 231 foods[27]. Importantly, many of the foods that were classified as ultra-processed are defined as having an acceptable or high nutrient quality by conventional nutrient standards. Such a striking lack of consensus has been echoed by others[6,28], and highlights how easily this seemingly simple classification scheme can be misinterpreted and could produce spurious associations, or create confusion among consumers when making dietary recommendations. In the rapidly expanding observational literature linking UPF consumption with health, few studies to date report either the process used or the level of agreement between coders when classifying foods into their respective processing classification level (i.e. inter-class correlations or other established measures of agreement between subjective attributions). The implication is that a researcher's own subjective interpretation of the NOVA classification or their beliefs about the healthfulness of processed food may shape their classification, and could potentially contribute to varied reported findings linked to health outcomes.

Future dietary associations between UPF intake and health should implement more rigorous approaches to measure inter-rater agreement by reporting the consistency of blinded processing classification attributions, using established metrics to demonstrate coder agreement. In addition, to further enhance the credibility of UPF designations and the self-report nature of the dietary intake measures, consumption patterns should be paired where possible with biomarkers of processed food intake. Emerging research has begun to propose novel bio-markers such as an industrial *trans*-fatty acid and the flavour marker 4-methyl syringol sulphate, a flavour marker of artificial 'smoke' flavour[29]. These biomarkers of UPF consumption can be linked to diet records of foods deemed to be highly or ultra-processed to enhance the objectivity of comparisons in the future. Taken together, these measures will help improve approaches and enhance the credibility of dietary epidemiological studies reporting associations between food processing and health.

Contribution of specific food groups to the NOVA 4 (ultra-processed) category

Epidemiological research categorises foods and beverages into 'food groups' to move beyond single foods and nutrients and inform a better understanding of the specific dietary patterns that link to specific health outcomes. In this way, we can conclude that regular consumption of a given food group is associated with positive or negative health outcomes. For example, 'dairy' describes a wide range of products including different milks, butter, yogurts or cheeses and regular consumption of this broad 'food group' has been shown to be positively associated with improved bone-health and reduced risk of fracture[30]. By contrast, the NOVA 4 category (UPF) currently covers a broad spectrum of different foods united only by the definition of 'foods of industrial creation', as described previously. The broad nature of this definition means the NOVA 4 category covers approximately 60 % of energy sold in many developed countries, although this prevalence varies between countries[31,32]. Importantly, unlike the example of dairy foods and bone health, where consumption of a single food group can be linked to specific health outcome, the diversity of the NOVA 4 category encompasses between ten and twelve different food groups, and includes everything from ambient dairy to extruded breakfast cereals and frozen meals[33,34]. Recent findings highlight the trouble with such a broad range of different food groups under the same ultra-processed umbrella. Across two studies from the Dutch *Life-Lines* cohort, UPF consumption was linked to all-cause mortality in a group of renal transplant patients[35], and separately to the incidence of type-2 diabetes among Dutch adults[36]. Among renal transplant patients, the NOVA 4 category corresponded to ten distinct food groups. Closer inspection of the relationship of individual food groups revealed that only two of the ten groups remained positively associated with all-cause mortality and included sugar-sweetened beverages/desserts and processed meats[35]. The other food groups either had no clear association or were negatively associated with mortality (i.e. protective), including starchy foods, refined grains breakfast cereals, prepared meals, cookies, sources of fat, fried foods, salty snacks, toppings, liquors and candies. A separate comparison reported a positive association between consumption of NOVA 4 foods and increased risk of type-2 diabetes where comparison of the food's groups showed the risk was highest when the dietary pattern is defined by cold and warm savoury snacks. A pattern of NOVA 4 'sweet snacks and pastries' was inversely associated with type-2 diabetes risk[36]. Grouping foods into the same category of NOVA 4 poses as risk when making dietary recommendations to public, as you may remove foods that are both a risk for and protective against the chronic disease outcome of interest.

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The central issue is that the NOVA 4 classification assumes that most of the food processing is deleterious for health, whereas closer examination of the food groups reveals this is not the case. There is now a growing acceptance that the NOVA system is not fit for purpose if it is to be applied to guide public health strategies or provide population-level dietary guidance[37]. Many of the main recommendations overlap with conventional nutrient profiling approaches that offer a quantitative comparison of foods based on their nutrient and energy contents[14,38]. Defining UPF by the purpose, 'number' or 'type' of ingredient rather than nutrient content results in recommendations to remove or reduce many foods with an acceptable nutritional quality. Removing all UPF from the diet is likely to have a significant negative effect on population health, where alongside removing nutrient-poor/energy-dense foods, it would also result in the falling intakes of food groups that have adequate nutrition and may offer protective effects to the development of diet-related chronic disease. Uniformly, discouraging the avoidance of all processed food is impractical, unrealistic and this approach lacks the nuance needed to holistically evaluate the significant contribution made by many processed and packaged foods to daily dietary intakes[39–41].

The good, the bad and the reformulated: the future of smarter food processing

Product reformulation is a priority of food manufacturers globally, with a focus on reducing salt, sugar, fat and energy density across products alongside efforts to enhance or improve nutrient profiles. National campaigns to reduce salt and sugar had prompted an industry-wide surge in reformulation that has led to a reduction in nutrients of concern across a broad spectrum of product categories. Often, more processed versions of the same food ingredient can be nutritionally better than less processed or home-made versions of the same item. For example, thermal treatment of milk or juices under vacuum reduces temperature-related vitamin and nutrient losses and improves the nutrient composition of the finished processed food[42]. Evidence from multiple meta-analyses of observational, animal trials and human RCT shows that switching from sugar-sweetened beverages to non-nutritively sweetened beverages can support both energy and BMI reductions, to an extent that is more effective than switching to water alone[43]. Previous research has highlighted the power of fortification and reformulation to significantly contribute to public health interventions aimed at increasing intakes, whether it be micronutrient fortified bouillon cubes[44] or enhanced whole grain intakes[45]. In Denmark, the consumer trends towards low-carbohydrate diets led to population-wide reductions in whole grain intakes. To counteract this, a public–private partnership organised a fortification campaign that produced population-wide increases in intakes of whole-grain foods. Over a 10-year period, national whole-grain intakes doubled with increases of 43 % in children and 27 % in adults, through the whole-grain fortification of industrially processed breads and breakfast cereals[46]. This targeted reformulation of these 'ultra-processed' foods resulted in a significant rise in whole-grain consumption at a national level. Industry-wide efforts to reformulate have led to population-level reductions in the availability of salt (NaCl) and *trans*-fatty acids, with associated improvements in cardiovascular risk[47]. Although by no means perfect, reformulation policies have been shown to be effective in shifting the availability of public health-sensitive nutrients such as salt, added sugar and saturated fat and increasingly, incentives, regulations and clear implementation strategies have been shown to support an improvement in the overall nutritional quality across product categories[48,49].

Most industrial processes are initially applied to improve the microbial stability and shelf-life of raw materials and enhance the nutrient content, palatability, digestibility and availability of nutrients in a way that often cannot be replicated in a domestic kitchen[18]. For example, non-thermal preservation techniques such as food irradiation, high pressure processing, cold-plasma or pulsed electric field processing are used as 'low-impact' processes to extend shelf-life and improve nutrient availability in a way that does not result in undesirable processing by-products or thermal destruction of temperature-sensitive nutrients[50]. Freeze drying removes water from raw materials through sublimation at low pressure, and has been shown to enhance rather than destroy nutrient quality and availability[51]. To naive consumers, these processes may appear intimidating[52,53], although they have clear and significant benefits in terms of shelf-life extension, reducing food loss, while enhancing sustainability and nutrient density. An emerging suite of innovative 'mild' processes with equally intimidating names is being pioneered to reduce energy and resource costs, and promote more sustainable food processing[54]. Techniques such as electro-static fractionation will result in less refined ingredients that utilise significantly less energy and can preserve innate matrix structures within raw materials while retaining nutrients. This shift towards milder processes is motivated by cost and environmental challenges rather than concerns surrounding the negative perception of ultra-processing on health yet highlights the potential benefits of smarter and more efficient processes in meeting growing food demand on a changing planet.

Reformulation and process innovation will remain a feature of global public health policy and a priority for food manufacturers that aim to produce healthy and sustainable products. Evidence from meta-analyses shows the efficacy of product reformulation, whether its switching to non-nutritively sweetened beverages to support reductions in energy intake and BMI[43], or product reformulation to reduce daily energy consumed[55]. Despite the demonstrated efficacy of reformulation and fortification efforts to enhance public health, there remains resistance among some opponents of food processing that believe that any effort to reformulate the food supply can only make a food even *more* ultra-processed[56]. Similarly efforts to support the protein transition from animal to plant-based sources of meat

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and dairy have been criticised as promoting a UPF environment[18]. Irrespective of these concerns, reformulation remains a fact of life, and will continue to be central to efforts to improve the nutrient density and sustainability of food production and distribution[37]. Understanding the mechanism(s) by which processed foods may impact health positively or negatively is therefore central to future efforts if we are to set a target for what needs to change in the way food is formulated and processed. Some of the putative mechanisms are summarised later that have been proposed to date to explain the properties of processed foods most linked to negative health outcomes.

Proposed mechanisms for the link between food processing, energy intake and health

Processing and formulation make considerable changes to a raw materials' composition and structure, and this has led to widespread speculation on the potential mechanisms by which processed foods can promote higher energy intakes and poorer health[57,58]. There follows a summary of some of the putative mechanisms linking processing and health, and the available evidence to support them including the role of additives, hyperpalatability, satiety glycaemic response, energy density and energy intake rate.

A role for food additives in diet-related chronic disease

Food additives are substances added intentionally to foodstuffs to perform certain technological functions, for example, to colour, to sweeten or to help preserve foods. Today, there are over 300 food additives approved for use in the European Union that are identified by an '*E-number*' that is always included in the ingredient lists of foods in which they are used[59,60]. The most common additives used are antioxidants (which are added to prevent deterioration caused by oxidation), colours, emulsifiers, stabilisers, gelling agents and thickeners, preservatives and sweeteners. Their addition enhances the microbial stability, shelf-life and organoleptic properties, and their use is strictly controlled by the European Food Safety Authority in the European Union, Food and Drug Administration and globally by regulatory bodies such as the Joint FAO/WHO Expert Committee on Food Additives. Since they are added to foods, new and existing additives undergo a rigorous approval process before they can enter the food supply[60] and their potential harmful effects are tracked over time and monitored once the additive is available.

Additives become more prevalent in foods as degree of processing increases and have been shown to be higher within the NOVA 4 UPF category[61,62]. Additives are always added to foods, so if they play a role in obesity-related diseases, there should be common biochemical pathways and mechanisms through which they can affect energy intake, either by promoting intake or dysregulation of appetite[63]. The use of food additives has been proposed as one of the potential mechanisms by which UPF consumption may promote metabolic dysfunction. A recent comparison of additive consumption within the Nutri-Net Sante cohort in France characterised the additive intakes in a large cohort of French consumers, and summarised these intakes by cluster from low to high intakes[62]. The authors proposed associations between additive intakes and the incidence of dietary chronic conditions such as obesity and type-2 diabetes. Importantly, when the reported levels of several additives were compared to those available and consumed in nature, the natural sources tended to be significantly higher in every case[63].

How such a diverse set of chemical compounds could be associated with common biochemical pathways in the aetiology of such a wide range of conditions remain unclear. Whereas there is some evidence to show emulsifiers may have a negative effect on a subset of those suffering from irritable bowel syndrome and Crohn's disease[64,65], these same sensitivities have not been observed in healthy populations. To date, there is no direct evidence of widespread effects of these food additives on the gut health of a healthy human population, although further research will continue to add to our understanding of this complex area[66]. Studies are now proposing links between the additive content of processed foods, intakes of emulsifiers and putative links with microbiome health[67–69]. Whereas it is important to inform these links with controlled hypothesis-driven research, there remains inconsistencies in the approaches used to compare the effect of specific food additives on microbiome composition, metabolites and health. There are also several obvious contradictions when linking the intake of specific food 'additives' to health via their impact on the microbiome. Take for example inulin, which is a soluble fibre that is frequently added to foods as a gelling agent, stabiliser and emulsifier in formulated packaged goods. Inulin is also promoted for its substantiated positive effect as an efficient pre-biotic with noted health benefits[70,71]. Inulin consumption has been shown to promote microbial fermentation to produce SCFA, lower gut pH that helps to inhibit pathogens, promotes the proliferation of beneficial bacteria and stimulates the production of a wide range of beneficial metabolites that positively influence health[72]. Evidence therefore supports the use of additives like inulin as having demonstrable health benefits that outweigh any speculative negative health outcomes linked to the use of additive more broadly.

Added flavours are common in packaged consumer goods and have been proposed as a marker of ultra-processing[29], and this has led to speculation that the added flavours promote overeating by increasing the hedonic appeal or by disrupting normal flavour nutrient learning to promote weight gain[73]. The suggestion is that sensory cues from highly processed foods no longer signal a foods' underlying nutrient content, such that synthetic and cosmetic flavours disrupt normal 'taste–nutrient' relationships and through this facilitate over-consumption. If this were true, then foods high in mono- and di-saccharides would not have a sweet taste intensity that reflects this concentration, or foods higher in NaCl would lack a salt taste intensity that matches

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their salt content, due to disruption of these taste–nutrient associations[74]. Data from a nationally representative survey of Singaporean diets were pooled to compare the perceived taste of a wide range of different foods to the content of the taste substrates (i.e. NaCl) across all levels of processing[75]. These results highlight that taste–nutrient relationships are maintained across all levels of food processing, including among foods classified as ultra-processed. Available data currently do not support claims made on the role of flavour additives in promoting food intake, although it remains important to question and monitor the safety of food additives and their potential impact on health. Ongoing research is further exploring the role of additives in promoting palatability and energy intake from processed foods (i.e. NCT05290064; NCT05550818).

Researching the specific impact of individual additives is extremely challenging due to the mixed nature of our diets, and the lack of quantitative information on additive intakes or exposure from either branded food databases or dietary records[63]. For example, it would be wrong to use inappropriate exposure assessments such as cross-sectional data and food frequency questionnaires to construct links between a foods' additive content and health. Using this as a basis for conclusions on the effect of additives on health or to support arguments to remove additives from the food supply is both inappropriate and unrealistic. If additive use is playing a role in promoting metabolic dysfunction, then research is needed to demonstrate this and regulations adjusted accordingly.

Hyper-palatability and energy absorption kinetics

Highly appealing foods may stimulate 'non-homoeostatic' eating where consumption is driven by pleasure rather than a homeostatic response to hunger[76]. Pleasure-driven intake may promote positive energy balance[77], and could potentially be a driver of larger meal size and increased intake. Beyond simply eating more of a food you 'like', it has been proposed that UPF promote a 'supra-normal' hedonic response to specific flavour and macronutrient combinations that exploits our neurobiological drive to seek and consume rewarding foods. This response has been termed 'hyper-palatability'[78] and is defined using food compositional criteria rather than subjective hedonic responses. According to the proposed definition, foods become hyper-palatable when they diverge from naturally occurring nutrient combinations to have a higher proportion of energy from combinations of three nutrient pairs (fat and sugar, fat and sodium, carbohydrates and sodium) that exceed pre-defined levels. These nutrient combinations are believed to increase the drive to eat and lead to over-eating. One issue with the term hyper-palatability is that it does not reflect the human subjective hedonic response to oro-sensory properties of the food being consumed and cannot be universally inferred from food composition alone. We would also predict a heightened hedonic response to palatable foods from individuals that go on to develop obesity, yet obesity is not reliably associated with heightened hedonic responses to specific foods. People across all weight classes consume more energy from foods they like, and less energy from foods they don't like, and this phenomenon has been studied and understood for many years[79–81]. There is also a circularity in the definition of hyper-palatability, since certain foods are classified as hyper-palatable because they lead to over-consumption, and to explain why these foods are over-eaten, the explanation offered is because of their 'hyper-palatability'.

Given the subjectivity of food preferences, it seems implausible that a set of predefined cut-off points for fat, sugar, sodium and carbohydrate combinations could be applied to maximise palatability and consumption for whole populations. If food producers are aware of the specific nutrient combinations that heightened product acceptance, then clearly they choose to ignore them, as 90 % of new product launches continue to fail[82]. Palatability, liking and consumer preferences are human subjective and emotional responses to the sensory and structural properties of foods as perceived during consumption, and it is not possible to predict this from compositional data in isolation[83]. Similarly, as a concept it is conceivable to impose the definition on individual food items, but our food environment has a rich complexity of mixed meals and dishes, comprising individual items in different combinations that are more or less palatable, which does not easily lend itself to a summary description of palatability. There has yet to be formal study that clearly demonstrates an elevated hedonic response to these nutrient combinations that is above what is already known about the influence of food liking on intake[81]. By contrast, the well-established phenomenon of sensory-specific satiety clearly demonstrates that the hedonic appeal of a food starts will decease rather than increase during consumption stimulating a desire for other foods and encouraging the consumption of a varied and balanced diet[84].

It has recently been proposed that UPF delivers energy more rapidly which may enhance food reward and reinforce dietary learning in a way that is different to equivalent energy consumed from less processed foods[85]. The proposed mechanism is that energy is more readily available in UPF compared to minimally processed foods, and that this in turn enhances the speed of post-ingestive signals on the gut–brain axis, wherein this change in reward kinetics stimulates a higher food reward and stronger hedonic reinforcement[86]. The premise is that the ready availability of energy in easily absorbable formats in processed foods could potentially influence the kinetics of energy uptake and stimulate stronger reward learning to further promote UPF consumption[86]. This is currently speculation and further research will be needed to demonstrate whether these effects are observed in controlled human feeding trials. Reserach is currently underway to test the role of the 'hyper-palatability' hypothesis and to better understand the role in energy intake, reward and learning (i.e. NCT05200845 and NCT05550818). In the interim, it is important to remain cautious and continue to question claims made in relation to the role of hyper-palatability in promoting energy intake, particularly when well-established phenomena

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such as the role of liking and sensory specific in moderating meal size and energy intake are well-supported by published data.

Are (ultra)processed foods all low in satiety and high in glycaemic response?

Another proposed mechanism is that refined carbohydrates from highly processed products derived from maize, wheat and rice promote over-eating by contributing energy, while also stimulating insulin release that clears blood glucose to adipose stores and promotes an increased hunger[87]. This model of obesity and metabolic dysfunction has been hotly debated in recent years[88]. The premise is that if you reduce rapidly digestible carbohydrate, blood glucose levels will not spike to promote insulin release, fat storage and greater hunger/lower satiety. However, the links to ultra-processing and poor health are tenuous and based on a small set of selective comparisons. Preliminary comparison of published glycaemic and satiety values was used to propose that all processed foods have low satiety and a high glycaemic index[89]. Using previously published glycaemic and satiety databases, foods were categorised by their degree of processing and compared glycaemic response and satiety ratio, resulting in a descriptive comparison that has been used to substantiate claims that UPF promote insulin release and are less satiating than minimally processed foods[89]. However, a recent report has highlighted that UPF may in fact have a lower glycaemic index than comparable foods that are classified as minimally processed[90]. Furthermore, there were no observed differences in post-meal satiety or later snack intake over 2 weeks in the only direct comparison of ultra- and minimally processed diets[91]. Indeed, some foods classified as ultra-processed can have lower fibre and protein contents than minimally processed foods, which could influence gastric emptying rate and neuro-endocrine satiety signalling, but this would need to be tested and is not the case across all (ultra)processed foods. To test this requires further research where energy and macronutrient matched meals are compared directly within the same population for potential differences in post-meal satiety. The implication is that mechanisms linking degree of processing to energy intake or satiety should be formally tested under controlled conditions to ensure mechanistic claims are supported by the appropriate data. In the absence of direct evidence, caution should be exercised when claims are made on the many of the putative mechanisms and proposed solutions that are not currently supported by published data. Future research should now focus on formally testing the role of specific nutrient and behavioural features of processed foods that may drive greater energy intakes and health outcomes.

The role of energy density (kJ (kcal)/g)

Both higher energy density and larger portion sizes have been shown to promote greater energy intakes, and this has been consistently shown across studies in adults, children, across genders, across meal occasion, food forms, macronutrient sources and in both acute and long-term studies[92–95]. In an RCT that compared ultra- and minimally processed diets, energy density was matched across diets at the level of the meal, although there were large differences in beverage and non-beverage energy density[96]. Participants were served an equivalent energy density on both the minimally and ultra-processed *ad libitum* diets (4·27 (1·02) *v.* 4·30 (1·03) kJ (kcal)/g) and were free to eat what they wanted from each meal, resulting in a higher energy density consumed on the ultra-processed diet (4·56 (1·09) *v.* 5·69 (1·36) kJ (kcal)/g). This may seem like a small difference, but a variation as low as 0·42 (0·1) kJ (kcal)/g has been shown to lead to increases of up to 418·4 (100) kJ (kcal) daily, suggesting that these differences were likely a significant contributor to the observed differences in daily energy intakes[97]. Energy density can often be higher in specific food categories that are classified as UPF, such as deserts or confectionary, but estimates suggest these products do not dominate daily energy intakes (i.e. <5 % of daily energy). It is important to note that reformulated UPF are often less energy-dense than comparable unprocessed products, as highlighted earlier. A recent meta-analysis highlights that efforts to reduce energy density have been successful at reducing energy intake[55], through the use of low and no-energy sweetened beverages or low-fat and low-sugar culinary ingredients.

It is difficult to establish a distinct role for food processing separate from the established impact of higher energy density in processed foods when these factors are not controlled for in observational comparisons. The single RCT to date to compare energy intake from ultra-processed and minimally processed diets had clear differences in non-beverage energy density served and consumed[91,97]. Reducing energy density in specific categories is a reformulation target for that has been used to inform public health policy in different countries[98,99]. Global efforts to reduce dietary energy density will continue. In terms of processing, to establish a focal point for action, it is first necessary to prove a distinct mechanism for the impact of processing on health that adds further to current knowledge of known elements within our food environment that promote excessive energy intake.

The role of energy intake rate in energy consumption from ultra-processed foods

A meal eating rate is described in g/min and is believed to be the product of the textural challenge posed by the food being consumed and an individual's internal drive to eat[100]. Extensive evidence from observational epidemiological studies consistently shows that self-reported eating rate is a predictor of higher energy intakes, body weight, adiposity and a wide range of cardio-metabolic risk factors[101–105]. This is further supported by findings from a series of controlled human feeding trials, where it has been shown that increasing the eating rate by approximately 20 % (g/min) results in a 12–15 % increase

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in *ad libitum* energy intake[106]. Previous research on the textural properties of the food environment has shown that food form and texture can strongly influence the rate of consumption, with eating speeds for solid foods as low as 10–12 g/min, and for beverages up to 500–600 g/min[107–112]. These differences in eating speed can significantly and consistently influence *ad libitum* energy intakes[104,110,113–115]. A simple example of this is the comparison of energy consumed from liquids *v.* solids, where it has been well established that high energy-dense liquids promote passive overconsumption compared to an equivalent energy load consumed as a semi-solid or solid[116–119]. Meal eating rate is driven by its texture properties[120] and may also interact with other known meal properties of meals that result in great intake, including portion size[121] and energy density[113].

Higher energy density can interact with food form and texture to influence the rate and extent of energy intake within a meal[75,115,122]. Higher energy density contributes to positive energy balance but makes a smaller contribution to the onset of satiation, meaning there is little adjustment within meal in response to consuming foods with a high energy density. In the one RCT that compared energy intake from ultra- *v.* minimally processed diets, participants consumed the ultra-processed meals up to 50 % faster (i.e. average energy intake rate 200·8 (48) *v.* 129.7 (31) kJ (kcal)/min), reflecting a combination of both softer textures and higher energy density among the foods in the ultra-processed diet. For certain UPFs, their textural properties may facilitate easier and more rapid consumption resulting in a faster eating rate[122], such that overconsumption may occur before gut–brain signals have time to communicate satiation[37]. Further research into the specific question of whether food texture or degree of processing moderates energy intake led to a comparison of *ad libitum* energy intakes from ultra- and minimally processed meals that differed in their texture and eating rate[115]. In the harder-texture condition, eating rates were reduced across both processing levels which produced a 21 % reduction in amount (g) and 26 % reduction in energy consumed. Research is now needed to clarify the role of food texture in moderating energy intake from processed foods, and an RCT is now underway to test whether the observed effect of food texture on intake from (ultra)-processed foods is sustained over time (https://restructureproject.org/).

Meal texture is more influential in driving intake within a meal than the degree of processing, leading to suggestions that the issue of texture and eating rate should be central in the development of new strategies to moderate energy intakes from processed food environment[123]. In recent years, there has been a proliferation in research on how to apply food texture changes to moderate eating rate[120,124] and apply this to reduce meal size and moderate the metabolic response to food consumed[105,125–128]. Future research should consider food texture-based strategies and manipulations to support consumers to reduce their eating speed and meal size. To achieve this, we will need further mechanistic studies to establish how these nutritive and behavioural properties differ across processed foods to better understand their contribution to higher intakes, and test whether changing these properties can help mitigate the risk of overconsumption.

Conclusions: moving 'beyond ultra-processed' food

The world now faces the triple threat of growing rates of diet-related chronic disease, rising food insecurity and growing concerns on the environmental impact of unsustainable food production practices. Processed and packaged food products are widely consumed and will continue to be a central component of the modern food supply and our diets in the future. The challenge now is to identify actionable ways to improve how our food is produced to reduce its impact on the environmemt, and ensure the nutritive properties of these foods meet the needs of a growing global population. The modern food system offers the necessary economies of scale and distribution channels needed to alleviate the risk of food insecurity for millions around the world. If food processing is to be considered an important element in supporting consumers to make healthier food choices, there needs to be a scientific consensus on the positive and negative contributions made by the variety of food processing techniques that includes an appraisal of its health and nutrient properties, environmental impact and the associated affordability considerations of dietary changes. Food processing utilises many different approaches that serve different functions, and it is inappropriate to define single unit processing operations as either 'healthy' or 'unhealthy', as all food production requires materials to undergo multiple diverse processing steps[18]. Because of this complexity, it is also not appropriate to summarise such a wide category as NOVA 4 as unhealthy, or to use the term 'processing' as a proxy index for the health effect a food. The breadth of the foods covered by the ultra-processed NOVA 4 category makes it difficult to implement clear and actionable nutrition guidelines that can inform healthier consumer choices, and risk removing nutritional adequate foods from the diet. Future approaches to define dietary strategies will also need to move beyond simply describing the degree of processing to cover the additional aspects such as the planetary impact of food production and consumption, nutritional properties of food and factors related to consumers' equitable access to a safe and affordable food supply. In this regard, the recently proposed sustainable-nutritious packaged foods[129] approach to describing sustainability, equity and nutrient density seems more objective and balanced than the simplified 1–4 scores of NOVA.

The benefit of food processing is that it makes food affordable, accessible and appealing, and yet these are now the same features that have raised concerns about how highly processed foods can promote excess intake. Consumers should be encouraged to limit consumption of several food groups, based on their composition rather than degree of processing. Few would support a public health policy aimed at producing foods that are both less appealing and more expensive[19], yet increasingly

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there are calls for additional taxes on UPF and tighter regulation and restrictions on the production and distribution of processed food. A sole focus on limiting people's access to processed foods may give rise to inappropriate solutions, and lead to the imposition of regressive taxes that will disproportionately affect the most vulnerable in society. Nutrition policies need to consider the context of consumption and the economic realities that many encounter when trying to adhere to diets that promote long-term impact on health and wellbeing. Food processing has granted access to safe, nutritious and appealing foods to millions of consumers globally, and setting nutritional guidelines that restrict access to the majority of foods purchased and consumed is both unrealistic and underestimates consumers ability to make informed decisions about the foods they purchase and consume. Understanding the properties of specific highly processed foods that promote higher consumption is now a research priority and will create new opportunities to go beyond traditional reformulation strategies to consider how sensory cues like food texture can directly influence the rate and extent of energy intake.

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Conflict of Interest

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Authorship

The author is solely responsible for the content of the current manuscript.

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