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ANNUAL REVIEWS

Annual Review of Nutrition

The Importance of Food Processing and Eating Behavior in Promoting Healthy and Sustainable Diets

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Abstract

Numerous association studies and findings from a controlled feeding trial have led to the suggestion that "processed" foods are bad for health. Processing technologies and food formulation are essential for food preservation and provide access to safe, nutritious, affordable, appealing and sustainable foods for millions globally. However, food processing at any level can also cause negative health consequences that result from thermal destruction of vitamins; formation of toxins such as acrylamide; or excessive intakes of salt, sugar, and fat. Research on ultraprocessed foods centers on food composition and formulation. In addition, many modern food formulations can have poor nutritional quality and higher energy density. We outline the role of processing in the provision of a safe and secure food supply and explore the characteristics of processed foods that promote greater energy intake. Despite the potential for negative health effects, food processing and formulation represent an opportunity to apply the latest developments in technology and ingredient innovation to improve the food supply by creating foods that decrease the risk of overeating.

Contents

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1. INTRODUCTION

In recent years, industrially processed foods have been associated with unhealthy dietary patterns and incidence of noncommunicable diet-related diseases such as obesity and type 2 diabetes mellitus (57, 66, 81). However, the evidence directly linking food processing to human health is weak. Determining the link between food processing operations and health outcomes is difficult for two reasons. First, almost all foods are processed to a certain degree (124), and second, few studies conducted to date have looked at the health impact of foods with the same composition that are processed in different manners. What also makes it hard to associate industrial processed foods with health outcomes is that many large-scale food processing operations, such as heating, freezing, or steaming, are not much different from techniques used to prepare foods at home (75), making it difficult to have a proper control for comparison. The ingredients used in some industrially processed foods are different from those typically used at home, and some authors have suggested that this could have negative health effects (65, 103). Additives such as colors, flavors, and preservatives are used to improve food safety, increase shelf-life, and improve consumer acceptability. These ingredients vary widely in their chemical compositions, so there would need to be a common biochemical pathway or mode of action for such a diverse set of molecules to disrupt metabolism or promote chronic conditions such as obesity and type 2 diabetes mellitus. Thus, it seems unlikely that all food additives negatively affect health or that categorizing very different types of foods as unhealthy simply because they contain additives is justified.

Industrially processed foods are also associated with intakes of high levels of saturated fatty acids, salt, and added sugars. For example, more than 70% of daily sodium intake originates from processed foods (83). Salt, sugar, and saturated fat not only affect health directly but also have been associated with changes in eating behavior that promote higher energy intakes. Many home-prepared foods also have high levels of saturated fatty acids, salt, and added sugars, making it hard to determine the impacts of industrially processed and home-cooked foods on health separately. Food processing has provided access to nutritious, safe, and affordable foods to millions of consumers globally but has also increased access to foods that are often high in salt, sugar, and saturated fat. For instance, products such as ready-made desserts and dessert mixes such as cakes, brownies, and icings make low-nutrient-density foods readily available and easy to prepare without needing to have access to multiple ingredients.

Because foods and food ingredients can affect health in so many ways, it is important to provide clear and unambiguous guidelines to consumers on the dietary habits to adopt or avoid. However, the complexity of food formulation and production makes it challenging to adopt simple classification systems that designate individual foods as simply healthy or unhealthy when consumed as part of a wider diet. Therefore, the purpose of this review is to provide a better understanding of what drives consumer food purchases, how foods are processed, how processing affects nutrient composition and sustainability, and how foods influence our eating behavior and energy intake. We aim to promote a rational approach both to guide dietary recommendations and to direct food reformulation and production to produce a healthier food supply.

2. WHAT DRIVES FOOD PURCHASES?

The International Food and Information Council has been conducting a consumer Food and Health Survey since 2012 to determine the main drivers of food purchases (see **https://foodinsight.org/2021-food-health-survey**). During this time, taste has consistently been the number one driver, followed by price/value, healthfulness, convenience, and sustainability. As with any operation that sells food, for a retail food palatability is key to repeat purchases and thus is critical for its economic success. Palatability (appearance, aroma, taste, and texture) can also be critical for increasing the consumption of healthy foods. Whole grains are widely known to be a healthy component of the diet (123). However, processing whole grains into products such as bread is more challenging than with white flour because the components of the wheat bran and germ compete for water, produce astringent flavors, alter gluten functionality, and decrease shelf-life due to the formation of oxidative rancidity from the lipids in the germ (110). Therefore, whole-wheat breads often need additional processing steps to increase loaf volume (enzyme treatments), decrease staling (emulsifiers), prevent spoilage by molds (antimicrobial agents), and decrease astringent off-flavors (sugars). This combination of processing steps and ingredients can greatly increase both palatability and consumption rates while also increasing shelf-life and reducing food waste (110).

Studies have shown that across a variety of processed and prepackaged breads, there were no significant differences in postprandial plasma glucose levels or in postprandial hunger ratings (3, 15). These breads ranged from white bread to whole-grain bread to pumpernickel bread; some contained food additives, and others did not. In the mid-2000s, Denmark saw a decline in carbohydrate-rich foods in association with media claims that low-carbohydrate/high-fat diets were healthier (64). With the reduction in carbohydrate intake came lower whole-grain intakes, which in the longer term could result in poorer health outcomes. To counter this trend, a private–public partnership organized a campaign to increase intake of whole-grain foods. Over 10 years, the Danish national whole-grain intake doubled, with an increase of 43% in children and 27% in adults (64). This successful intervention caused significant population-level increases in whole-grain intake that could have a substantial and positive effect on public health (60, 109). The food categories that were the primary focus of the campaign were industrially processed breads and breakfast cereals, which, when fortified with whole grains, would have been classified as highly processed foods.

Price can drive buying decisions, especially when consumers have limited means to purchase food. Economies of scale from large-scale food production can decrease the cost of foods. When raw materials are purchased in bulk, processing operations produce less waste and are energy efficient; waste streams can be converted to value-added products (e.g., whey proteins); and packing, processing, and food ingredients can increase shelf-life and thus decrease food waste, in turn significantly decreasing the cost of food products (45). The success of agri-food systems has resulted in a dramatic decrease in the amount US consumers spend on foods. The percentage of disposable income spent on food decreased from 20–25% in the 1930s through 1950s to approximately 10%

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in 2020 (32). Unfortunately, low-income US populations spend more of their disposable income on food. Populations in the lowest quintile of earnings spend 27% ($77/week), those in the middle quintile spend 12% ($125/week), and those in the highest quintile spend 7% ($235/week) on food (32). Healthy, fresh foods can sometimes be more expensive, making it more challenging for lower-income populations to access healthy diets (41).

Convenience is also one of the top drivers of food purchases, as the pressures of work, commuting, and recreational and family time make it challenging for many individuals and families to spend much time on purchasing and cooking foods (68). From 2014 to 2017, Americans spent an average of 44.1 min/week on food shopping and 27.5 min/day on food preparation (2). Women (37 min/day) were more engaged in food preparation than men (17 min/day). The amount of time spent preparing foods has steadily decreased over the years. For example, in 1965–1966, women spent 113 min/day preparing food (105). In the United States, single parents and low-income families spend the least amount of time on food preparation (68, 69).

Food palatability, cost, and convenience are strong drivers of consumer choice but do not directly relate to the nutritional value of a food. Nutritional considerations are also important in food purchases, though they can be overcome by other drivers such as food preferences, ease of preparation, and cost. When faced with competing demands on time and economic resources, many low-socioeconomic-status consumers may opt for convenience and taste over nutrient density. Easy and affordable access to healthy and balanced diets remains aspirational for many. A study using the Healthy Eating Index (HEI) to compare diets found that the highest-income populations had an HEI of 68, compared with 52 for the lowest-income population. The high-income populations also purchased more fruit, vegetables, whole grains, dairy, and seafood (41). Nevertheless, we note that processed foods contribute significantly to nutrient intakes (30, 48, 51, 130) and represent an important and affordable source of energy and nutrition for consumers across a wide range of socioeconomic categories.

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3. FOOD PROCESSING

In order to understand the impact of food processing on society, it is important to know how and why foods are processed and how that processing affects the health and wellness of the food supply. This section is not intended to give a highly technical overview of food processing but rather to help people outside food science have a better understanding of why foods are processed and how this processing affects nutrition.

In its simplest definition, food processing encompasses any change in the biological materials we use for food. Fire was one of the first tools that allowed humans to begin processing their foods, along with operations such as removing undesirable components by peeling (fruits and vegetables), trimming (meats), dissecting (seafood), and dehulling (grains) (40). Fire was also used to dry and smoke foods, extending shelf-life by inhibiting the growth of spoilage microorganisms through a decrease in water activity and the production of antimicrobial compounds, such as phenols, from smoke. Food fermentations were another early form of food processing, dating to approximately 9,000 years ago (89). The first examples were likely accidental, such as in spontaneous fermentation of milk and fruits, where conditions allowed wild yeast and bacteria to grow quickly and prevent the growth of spoilage organisms and pathogens.

Food production often includes the addition of ingredients to improve quality, enhance nutrition, and extend shelf-life. Salt was likely one of the first processing aids to have a major effect on food production, as it can dramatically preserve foods for many months and decrease dependency on seasonal food availability. Addition of salt preserves foods by decreasing water activity and directly inhibiting the growth of spoilage organisms. In addition, salting creates a selective growth

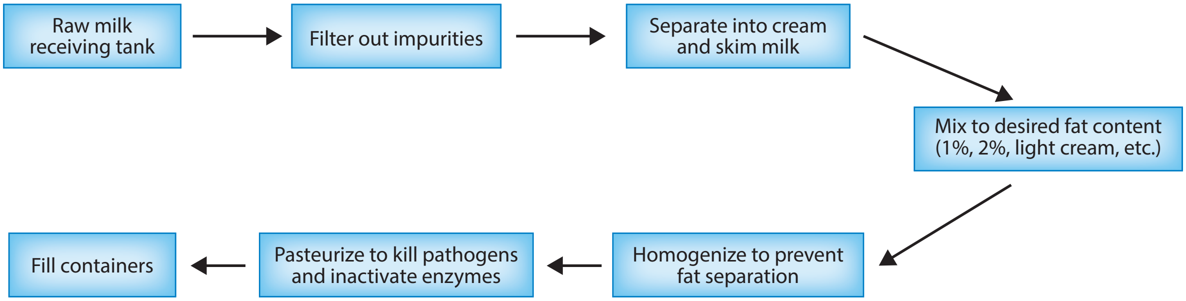

Figure 1

The unit operations involved in the processing of fluid milk products.

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environment for beneficial microorganisms that makes it easier to control processing by fermentation (89). The most common of these examples is the use of salt to create conditions for the growth of lactic acid bacteria that can decrease pH and change food texture, taste, and color as well as increase the shelf-life of vegetables (e.g., pickles and sauerkraut), dairy products (e.g., yogurts and cheeses), and meats (e.g., salamis). In this regard, unlike in other domains such as digital media, innovations in food processing operations do not necessarily replace old methods, and such developments can be viewed more as evolution rather than extinction (102). As such, there is often less pressure to accept novel or disruptive innovations in food processing and formulation, which may explain consumers' hesitancy to adopt new food technology innovations despite clear benefits (75).

Today, food processing is described in terms of unit operations (31). Unit operations are the individual steps used to produce foods, such as heating, cooling, drying, and extrusion. Many unit operations in large-scale food production are similar to steps used in home cooking. Commercial breads are mixed, risen, baked, and cooled, similar to what is done at home but on a larger scale. Most foods are processed by multiple unit operations. For example, milk is produced by at least six: filtration, separation of cream and skim milk, blending, homogenization, pasteurization, and packaging (**Figure 1**). Flour milling and refining comprise more than 15 unit operations, including multiple steps to remove impurities (e.g., nongrain plant material, stones, metals); tempering to soften the endosperm; grinding; rolling; separating bran, endosperm, and germ; sifting; bleaching; enriching; and packaging (85). Some unit operations are similar across food categories, such as pasteurization of dairy products, juices, beer, eggs, and seafoods. However, others can be very different from home cooking and are limited to several food categories, such as twin-screw extrusion of ready-to-eat breakfast cereals and high-pressure processing of seafood and dips.

Because so many unit operations used in the processing of foods serve various functions, it is not appropriate to define single unit operations as healthy or unhealthy, as most foods have multiple unit operations. Because of the complexity of food processing, it is also not appropriate to use the term "processing" as a proxy for the effect a food has on health. For example, both low-sugar/high-fiber and high-sugar/low-fiber breakfast cereals can be processed in similar manners, but their nutritional content can differ dramatically due to differences in formulation. Conversely, frozen and canned vegetables and beans are processed by very different unit operations but can have similar nutritional content (see **https://fdc.nal.usda.gov**).

3.1. Impact of Food Processing on Nutrition and Safety

Cooking and processing of food change nutrient composition and nutrient bioavailability in many ways (124). For example, cooking legumes and grains inactivates protease and amylase inhibitors that inhibit digestion (85). Corn can be processed by soaking in an alkali solution (yielding masa) to improve its functional properties so that it can be used in tortilla production. This alkali soaking, known as nixtamalization, also improves nutrition by partially gelatinizing starch, solubilizing fibers, and increasing the bioavailability of riboflavin and niacin (108).

Therefore, processing can make foods more appealing, more digestible, and safer. However, it can also change the foods' nutritional composition, especially through the thermal destruction of vitamins (43, 46). In many cases, cooking processes in food processing plants and in home/food service cooking operations are similar, so the resulting nutritional changes should be similar. Unfortunately, to our knowledge, such direct studies have rarely been conducted. In some cases, industrial equipment can decrease nutrient losses by comparison to the same processes in the domestic kitchen. For example, milk and juices can be concentrated by thermal removal of water under vacuum to decrease the boiling point of water as well as with heating technologies such as microwave to increase the speed of heating. These technologies decrease the rates by which vitamins are degraded and improve the nutrient composition of the finished processed food (14).

Cooking is often done to make food safer by killing pathogens. Pathogen destruction is very sensitive to temperature, so it can be accomplished by heating at high temperatures for short periods of time. For example, ultrahigh-temperature (UHT) pasteurization can kill pathogens in milk by heating to 135°C for only 2–5 s. Conversely, vitamin degradation can be less sensitive to temperature but more affected by the time of heating. As a result, processing operations that heat for short periods of time at high temperatures will quickly inactivate pathogens while having less of an impact on vitamin decomposition (31). Industrial equipment that can accomplish this rapid heating includes UHT pasteurization machines, advanced convection oven technologies, impingement ovens, high-pressure cooking units, and steam injection ovens, all of which can cook faster than is possible in home cooking operations.

Nutritional composition can also change as a result of processing operations that separate raw materials. These steps include removal of skins and hulls that are high in dietary fiber (grains, fruits, and vegetables) and removal of fat (meat trimming). Food processing is also used to separate food components to change their sensory properties, nutritional composition, cooking properties, and shelf-life. Examples include separating milk to create a series of products with varying fat content and thus caloric density, refining oils to remove undesirable minor lipid-soluble components (free fatty acids, toxins, and colors), and milling grains to make different kinds of flours. Separation also includes removal of water from numerous foods, which decreases water activity so as to inhibit microbial growth (dried fruits, vegetables, meats, and seafood) and to decrease product weight and bulk so as to increase the sustainability of transportation (juice concentrates and dried milk). Nutritional changes in these products include nutrient concentration (drying), fat reduction (dairy products), and vitamin destruction (high-temperature drying).

Separation processes such as milling of grains can cause the loss of important nutrients, so the end products are sometimes enriched to replace some of the lost nutrients. Wheat was originally milled into white flour because the latter has a milder taste and better functionality; milling can also help remove harmful molds from the husk and remove the germ, which is high in polyunsaturated fats that decrease shelf-life via lipid oxidation (85). However, removal of the wheat bran and germ results in the loss of B vitamins and iron. During World War II, countries required white flour to be enriched, as white flour was widely consumed and enrichment is an efficient way to deliver these important nutrients (52). Similarly, removal of rice bran can remove nutrients, so rice is often soaked, steamed, and dried before the husk is removed. This process helps transfer some of the nutrients from the husk into the endosperm of the rice grain to improve the nutritional profile of so-called converted white rice (74).

Some modern industrially processed foods have raised concerns, but in reality, many large-scale food processing operations are better controlled than home cooking operations and thus result

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in lower nutrient losses and produce fewer toxic compounds. For example, cooking can cause the formation of toxins such as acrylamides, furans, acrolein, and heterocyclic amines (124). Industrial food processing operations use various techniques to make sure foods are cooked consistently so that all products are of similar quality. In contrast, overcooking of foods by home cooks can lead to the consumption of more heat-developed toxins and destruction of nutrients. Industrial processing also maintains greater control over raw materials, which can further decrease the formation of toxins. For example, acrylamide is a neurotoxin produced through the reaction of reducing sugars and the amino acid asparagine. This reaction increases with increasing temperatures. Potato chip manufacturers can decrease acrylamide levels by minimizing the amount of reducing sugars in the potatoes, using potato varieties with low asparagine levels, and cooking at as low a temperature as possible. These combined measures have decreased acrylamide levels in European potato chips by 53% from 2002 to 2016 (88). Gonzalez-Mulero et al. (44) found that the level of acrylamide in potato chips depended on where they were cooked; home kitchens had a higher level than food service, which in turn had a higher level than industry. The authors proposed that this variation arose from differences in cooking temperature, characteristics of the raw potatoes, and industrial use of a rinsing operation that removes reducing sugars.

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3.2. Processed Foods and Sustainability

Industrially produced foods are often more sustainable compared with home-prepared foods. Modern processing equipment is much more efficient at heat transfer; can be conducted under vacuum to decrease the boiling point of water; and often uses steam and pressure to cook faster, thus using less energy than home cooking. Energy conservation in food processing plants is often driven by costs and is critical for profitability and, thus, a major focus in equipment design and plant management. Processes such as drying, pasteurization, aseptic processing, oil refining, and modified atmosphere packaging increase shelf-life and thus decrease food waste. In large-scale processing, food plants create large amounts of by-products that can be converted into energy (methane production), made into additional foods or ingredients (whey proteins and grapeseed oil), or used for animal feed, thus decreasing food waste. One example is the production of butter. Butter is made from cream that is initially separated from the skim milk fraction, leaving skim milk as a by-product. This skim milk can be used in the edible milk supply, but often its production exceeds demand, so it is dried into skim milk powder. The drying process decreases food waste and increases food availability, since skim milk powder has a long shelf-life and can allow dairy products to be distributed internationally to countries with low milk production. Also, food processing is often conducted continuously, with production lines operating for many days in a row. This means that equipment needs to be cleaned less often and technologies such as clean-in-place are highly efficient, resulting in less water usage and subsequently less water treatment in sewage facilities.

There are many challenges to further increasing the sustainability of food production, increasing energy efficiency, reducing food waste, and meeting the needs of a rapidly growing global population. These include increasing the sustainability of animal production by optimizing genetics and animal nutrition, reducing the release of greenhouse gases, and using land unsuitable for plant production (92). However, the overall nature of animal food production means that it will likely never be as sustainable as plant foods; thus, it will be important to develop technologies to replace animal products with plant-based alternatives (71). To be widely incorporated into the diet, these plant-based alternatives must meet the same criteria as other food products, including acceptability in taste and texture, appropriate cost and value, convenience, and strong nutritional profiles.

Proteins are an important component of animal foods in that their unique biochemical and functional properties impart the textures we expect in dairy and meat products. For example, the milk protein casein is highly phosphorylated, allowing it to interact with divalent cations such as calcium to form aggregates and produce the textures we expect in yogurt and cheese. Muscle proteins, such as actin and myosin, are elongated, water-insoluble proteins that have a unique mouthfeel, which produces both the textures we expect in cooked meat and the functionality needed to produce foods such as sausages.

Most readily available, nonallergenic plant proteins are globular, water-soluble proteins that are minimally phosphorylated (71). Thus, to produce the necessary textures associated with animal foods, technologies are needed to alter the shape and surface charge of plant proteins to get them to form aggregates similar to those in many animal foods. Because of their solubility, plant proteins are capable of mimicking animal products such as milk. However, these products are not nutritionally similar to cow's milk, so they must be fortified with nutrients such as calcium and vitamins A and D. To mimic the sensory attributes of meat, plant proteins must be processed in a manner that denatures and elongates the proteins so that they form aggregates that are filamentous and have a chewy texture. This is typically done with extrusion and similar food processing technologies. However, by themselves these texturized proteins do not have the color, flavor, mouthfeel, and nutrition of meat products. Therefore, to gain consumer acceptance, they need added color (plant pigments or heme proteins), flavor (heme proteins, salt, yeast extracts, and natural flavors), moisture enhancers (fat, starches, cellulose, gums, and lecithin), and nutrients (iron; zinc; and vitamins B3, B6, and B12). These processing techniques and ingredients would place plant-based foods squarely in the highly processed foods category. Thus, dismissing all of the latest developments in sustainable food production and food reformulation as unhealthy may discourage consumption of new healthy and sustainable food products (122).

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4. PROCESSED FOOD AND ENERGY INTAKE

4.1. Classifying Food Processing and Formulation

The nutrient and energy content of foods have been the basis of dietary guidelines and population advice on managing energy intake and controlling weight gain since 1980, when the first US dietary guidelines were issued by the US Department of Agriculture. Recently, the focus has shifted away from a food's nutrient content to the degree to which it has been processed as an indicator of its nutrient quality (81). This shift arose from increasing concerns about the rising rate of diet-related chronic diseases, such as type 2 diabetes mellitus and obesity, and the concurrent increase in global consumption of industrially processed foods (e.g., 69). These foods have been described as ultraprocessed foods (UPFs), a term first used and defined by the NOVA classification system, which is the most widely publicized system that correlates how a food is processed with health outcomes (81). The NOVA system classifies foods as unprocessed or minimally processed foods (NOVA 1), processed culinary ingredients (oils, sugar, and salt) (NOVA 2), processed foods (NOVA 3), and UPFs (NOVA 4). Processed foods are defined as products made from NOVA 1 and 2 added together, while UPFs are described as "formulations of ingredients, mostly of exclusive industrial use, typically created by series of industrial techniques and processes" (79, p. 937). Numerous studies have suggested that UPFs have negative health implications and that their consumption is associated with higher body mass index (BMI) (53, 128).

The NOVA definition of UPFs has evolved considerably since its introduction. Initially it focused exclusively on food processing but has shifted to incorporate food formulation and composition (42). Despite public health recommendations to avoid processed food, almost all advice centers on avoiding specific nutrients like fats, sugars, and salt rather than reducing processes such as fermentation, spray-drying, or extrusion. This has led to debate on the usefulness and application of such a broad definition in public health research and policy (42, 52). Different classification systems, including NOVA, International Food Information Centre (IFIC), European Prospective Investigation into Cancer (EPIC), and University of North Carolina (UNC), are used to compare degrees of processing, and the system used to classify dietary intakes can significantly affect the strength of association between processed food and disease outcomes. Extensive evidence exists on the negative health impact of excessive consumption of nutrients such as salt, sugar, and fat, yet today it remains unclear whether the way foods are processed affects how they modulate diseases, independent of their composition. In the below discussion, we take UPF to reflect food formulation and nutrient content rather than simply the processes by which a food is manufactured.

4.2. Ultraprocessing, Energy Intake, and Chronic Disease

Both cross-sectional and longitudinal association studies (e.g., 6, 59, 93, 99) have associated the consumption of processed foods and UPFs, as defined by NOVA, with higher chronic disease risk and greater all-cause mortality. These associations are important because diet is a modifiable risk factor for many noncommunicable diseases, such as type 2 diabetes mellitus or obesity, that could be reduced or prevented at the population level through public health recommendations to promote choices that limit the consumption of foods classified as unhealthy or linked to diet-related conditions. One such longitudinal study is the SUN cohort from Spain, which profiled a large group ($N = 8{,}451$) for almost 9 years and concluded that increased UPF consumption is associated with greater risk of overweight and obesity. The recommendation from this finding is that efforts should be made to reduce processed foods and adopt a traditional Mediterranean diet (78).

Using a similar approach, the PREDIMED-PLUS cohort ($N = 6{,}874$) classified longitudinal diet and health data according to the four most widely accepted classification systems for processed food (i.e., NOVA, EPIC, IFIC, and UNC) to compare processed food intakes and health outcomes. Only the NOVA classification system showed clear associations with increased disease risk, whereas comparison with the other food processing classification systems did not (69). This finding suggests that, whereas associations among food formulation, energy intake, and health outcomes clearly exist, the strength of the outcomes linked to food processing operations is contingent on the criteria of the classification system used to categorize the degree of processing and formulation.

Other observational epidemiological studies have found associations between consumption of UPF and obesity, cancer, and a wide range of noncommunicable diet-related chronic diseases. However, most of these studies did not control for dietary energy density when making comparisons, and in the few studies that did control for potential confounders, associations between processed food intake and consumption of saturated fat and sodium were attenuated (29). Given that approximately 60% of dietary calories in developed countries are provided by foods classified as processed or ultraprocessed (132), it is unlikely that a recommendation to avoid all processed foods would be successful. Similarly, previous studies highlighted the significant role of processed foods in achieving daily nutrient intakes recommended by dietary guidelines (30, 51, 130). Recommendations to cut processed foods could also remove significant sources of important nutrients from the daily diets of millions of consumers. For example, fortification of flour with B vitamins provides affordable access to nutrients, decreasing the incidence of diseases such as beriberi and pellagra (30).

Association studies and prospective cohorts provide estimates of the effect size of the impact of processed food dietary patterns and suggest causal links, but they do not directly compare their effects in a controlled way or clarify the reasons underlying the observed relationships. Randomized controlled trials (RCTs) offer more direct insight into the impact of consuming processed foods on health. To date, only one study comparing energy intake between unprocessed and ultraprocessed

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diets in a controlled way has been conducted (47). This study was a crossover, inpatient, ad libitum feeding RCT conducted over 4 weeks in the controlled setting of a metabolic ward. Participants ($N = 20$) were randomized and asked to follow one test diet for 2 weeks and then switch to the other in order to compare the impact of processed food on daily and cumulative energy intakes. Importantly, the participants were free to eat as much or as little as they liked at each meal, and when designing the diets, the researchers took care to ensure that more than 80% of the calories came from familiar foods that were classified as either unprocessed or ultraprocessed using the NOVA scheme. Both diets were matched for carbohydrates, fat, protein, fiber, and salt content, and the total energy density served was equivalent, though there were large differences in energy density consumed. Results showed consistently higher energy intake on the ultraprocessed diet arm, with an average of 508 kcal/day and an average weight gain of 0.9 kg, comprising mostly fat mass, with equivalent weight loss on the unprocessed arm (47). The trial provided a carefully controlled comparison of the sustained impact of degree of processing on energy intake but was not designed to determine the mechanism underlying the observed differences in energy intake. This led to speculation about the potential reasons for the observed differences in energy intake, and several putative mechanisms have been proposed to explain why ultraprocessed diets may promote higher energy intake. Some of these proposed mechanisms are discussed in subsequent sections.

4.3. Energy Intake from (Ultra)Processed Food

Consistent reports of higher energy intakes from ultraprocessed foods have led to speculation about the food properties and eating behaviors that promote greater intakes. Here we review some of the putative reasons for higher energy intakes from diets high in UPFs.

4.3.1. Food processing and taste–nutrient relationships. The predominant taste quality perceived during consumption of a food is often associated with its nutrient and energy content and is believed to help inform our food selection, guide our perception of caloric density, and direct our intake behavior to counteract dietary imbalances (70, 126). For example, mono- and disaccharides taste sweet, and their relative intensity can be an indication of a food's sugar content and of the energy that will be derived on consumption (118, 127). Over time, sweetness becomes predictive of sugar and carbohydrate ingestion and stimulates insulin release (49, 54, 112). These relationships are learned, so any disruption of the link between sensory cues and nutrient content could disrupt these learned associations and affect intake behavior. Researchers have proposed that nonnutritive sweeteners may disrupt natural associations between sweet taste and energy intake, priming appetitive responses and stimulating greater energy intakes (86, 101). Findings from animal studies that nonnutritive sweeteners disrupt natural associations between sweet taste and energy intake were not confirmed when sweeteners were substituted for sugar in human studies. Moreover, numerous meta-analyses have demonstrated that low- and no-calorie sweeteners lead to a significant reduction in dietary energy intake and body weight (e.g., 96). Regardless, researchers have proposed that this is one mechanism that could explain why processed foods are associated with sustained higher energy intake, as processing and formulation with "cosmetic" flavors and additives may disrupt natural taste–nutrient relationships and stimulate passive overconsumption of calories by disrupting our natural ability to self-regulate food intake (80).

This line of reasoning has been extended to artificial flavors in processed foods. A series of dietary association studies have raised concerns that that these flavors and additives may disrupt traditional taste–nutrient relationships and interfere with metabolic and biochemical pathways to promote energy intake (106). Comparisons of taste–nutrient relationships have been extended to whole-diet comparisons within a population-based cohort (*n* = 7,011), and a recent study demonstrated that a food's predominant taste quality remains a strong, significant predictor of its macronutrient content (114). These taste–nutrient relationships persist but differ in strength across diets that differ in processed food consumption. For example, highly processed foods often contain more salt; as such, the link between salt content and salt taste intensity tends to be stronger among foods within this category.

Beyond taste–nutrient and additive concerns, there are several plausible reasons why energy intakes may be higher when consuming a diet high in processed foods. Below, we describe potential mechanisms including (*a*) consumption of energy-dense liquid calories with low satiety, (*b*) higher eating rates (measured in grams per minute) and energy intake rates (kilocalories per minute), and (*c*) the role of palatability and fat blindness at high taste intensity.

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4.3.2. Food form, eating rate, and energy intake rate. The sensory properties of foods and beverages are an important determinant of food choices, eating behaviors, nutrient digestion, and metabolism (72). On a calorie-for-calorie basis, liquid foods have a lower satiating capacity compared with equicaloric semisolid or solid foods (19, 61). This is due to the cognitive, orosensory, and gastrointestinal effects of food form, which not only influences nutrient availability, absorption, and metabolic response but also can influence the way a food is consumed and the extent of its consumption (23, 133). Liquid foods have a significantly higher eating rate and lower orosensory exposure time than do semisolid or solid foods, with a reported range of 200 to 500 g/min for liquid foods versus a narrower range of 10 to 120 g/min for solid foods (37, 39, 125, 126). Thus, high-calorie liquid foods result in rapid energy intake (kilocalories per minute), which reduces the ability to regulate intake and provides lower satiety per kilocalorie consumed in comparison to the same energy when consumed as solid foods (18, 20). This rapid intake of liquid calories has been implicated in the etiology of obesity; widespread public health guidelines state the need to reduce liquid calories and discretionary calories consumed as liquids (20, 67, 87).

Consuming foods at a faster rate is one reason that increased energy intakes from liquid foods, and faster eating rates have been associated with a higher rate of obesity and adiposity and with higher cardiometabolic risk (113, 116). A meta-analysis of studies that measured both eating rate and energy intake concluded that faster eating rates promote greater energy intakes (94). The effect of faster eating rates is further exacerbated when faster eating is combined with higher energy density, and it consistently promotes higher energy intake by increasing the energy intake rate (measured in kilocalories per minute) (56, 72). Faster eating has also been associated with higher energy intakes and lower satiety per kilocalorie consumed, making it more likely to overcome regulation of intake and to increase ad libitum energy consumption (22, 35, 36, 61). At a population level, eating at a faster rate (113) and consuming foods that both are high in energy density and have textures that enable them to be consumed rapidly have been associated with the highest rates of obesity and adiposity (115, 117).

A recent RCT by Hall et al. (47) was designed to compared energy intake for both unprocessed and ultraprocessed diets, rather than to establish the causal mechanism underlying increased intake. Despite large differences in daily energy intakes, there were no clear differences in metabolic markers following consumption of each diet. Specifically, there were no significant differences in glucose, insulin, or resting levels of neuroendocrine satiety markers. This finding led to speculation that differences in energy intake were likely prompted by behavioral factors, rather than by a metabolic disruption of energy intake (38). During the trial, meals on the ultraprocessed diet arm were consumed at a consistently faster rate (37 versus 30 g/min), leading to more than 50% higher calorie consumption (48 versus 31 kcal/min) (see figure 2f of 48). The implication is that a potential route by which UPFs promote higher energy intake is through a combination of faster eating rates (116) and higher energy densities (97).

A separate analysis pooled eating rate data (in grams per minute) from five published studies and combined them with details of each food's energy density (in kilocalories per gram) to investigate trends in energy intake rate (in kilocalories per minute), across different degrees of processing, for a large sample ($N = 327$) of everyday food items (38). Using the NOVA classification, the comparison showed that average energy intake rate tends to increase with the degree of food processing, from unprocessed (35.5 ± 4.4 kcal/min) to processed (53.7 ± 4.3 kcal/min) to ultraprocessed (69.4 ± 3.1 kcal/min). Importantly, the findings also highlighted wide variation within each processing category, where food texture and energy density drive the energy consumption rate. For example, unprocessed freshly squeezed orange juice is high in fructose and can be consumed rapidly, promoting a higher energy intake rate, whereas ultraprocessed soda beverages sweetened with nonnutritive sweeteners can be consumed quickly but with no energy. Powdered vegetable soups are an example of a highly processed low-energy-density food that is consumed slowly (9 kcal/min) (38). Food processing and formulation can be applied to increase or decrease the rate of energy consumption. Many processes increase texture and slow food intake (i.e., baking, extrusion), while the use of low-calorie ingredients makes it possible to replicate the sensory experience of caloric components without the associated caloric load (i.e., nonnutritive sweeteners with soluble fiber bulking agents). These wide variations in energy intake rate observed within the ~330 foods compared make it difficult to show a specific role for processing and formulation in increased energy intake rate. These findings highlight the potential for food processing and product reformulation to either increase or decrease a food's energy intake rate and the degree to which a food is consumed (121).

Extensive processing and deformation can damage the structural integrity of a food matrix, which might be another mechanism by which processed foods can disrupt metabolism and affect health (5, 80). Foods with weaker structures can deform more readily during consumption and are consumed at a faster rate, often producing higher postprandial glucose and lipid responses. Changes within the food matrix also alter nutrient availability and influence postprandial metabolic kinetics (1). For example, research has shown an attenuated lipid response and lower cholesterol when an equivalent nutrient load was consumed as cheese rather than as individual nutrients (120). In this example, food processing (of milk into cheese) offers postprandial advantages when making nutrient-matched comparisons, and there are many other examples within the processed foods category. As such, the food matrix integrity can influence metabolic responses, and currently there is a lack of evidence to support a systematic negative effect of food processing on the food matrix that links processed food consumption with deleterious metabolic responses. Further controlled feeding trials are required to systematically understand the impact of food processing and matrix structure on metabolic responses for the same nutrient load.

Extensive recent research has focused on the importance of a food's texture in moderating the rate and extent to which calories are consumed within a meal and flow through our diets. Bulk, surface, and geometrical properties of semisolid and solid foods influence oral processing behaviors such as sip or bite size, number of chews per bite, and orosensory exposure time (i.e., oral residence, transit time, and total duration from ingestion to swallowing), highlighting new opportunities to use food texture to slow the rate and extent of energy intake (9, 36). Increasing masticatory activity by changing food texture may be a promising strategy to influence energy balance (50), and the impact of specific textures on oral processing behavior has been well described (36). For example, soft textures that fragment easily and agglomerate quickly are associated with faster eating rates, whereas foods with higher moisture or fat content require less chewing to achieve sufficient lubrication for safe swallowing, promoting faster consumption (36). Manipulating food texture in

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controlled feeding trials reduces both eating rate and the amount of energy consumed ad libitum to satiation (10, 39, 72). Taken together, these findings suggest that food form, texture, and energy density, and the resultant eating behaviors, are likely to play a role in observed differences in energy intake from UPFs.

4.3.3. Hyperpalatability or fat blindness? Studies linking UPF consumption to excess energy intakes offer several mechanisms by which processing and formulation promote intake. One proposed mechanism is to design processed foods to be highly palatable and lower in satiety, which can promote overconsumption (34, 82, 121). The idea that consumers struggle to resist the hedonic appeal of these low-satiety processed foods, and that processes and formulations make a food hyperpalatable, is an attractive concept, as it shifts the locus of control for energy intake away from the consumer to the food producer. However, available evidence does not show a clear trend for a supranormal or hyperpalatable sensory response to processed foods above and beyond those observed in macronutrient- and energy-matched unprocessed foods. To date, the only RCT that compared meal palatability and energy intake from unprocessed and ultraprocessed diets (47) found no consistent differences in ratings of meal pleasantness between the unprocessed and ultraprocessed diets.

It is well known that increasing the hedonic appeal of a food or beverage will promote its intake during a meal (e.g., 13, 73, 131). Greater palatability has been associated with increased intake for meals in both the unprocessed and ultraprocessed diets (47). A food's sensory intensity may directly influence energy intake, independent of a food's palatability (**Figure 2**), but our current understanding suggests that greater sensory intensity will lead to reduced intake, as opposed to promoting a greater drive to eat (72). For example, a higher saltiness intensity reduced ad libitum energy intake by ~9% from test meals of tomato soup that had equivalent palatability,

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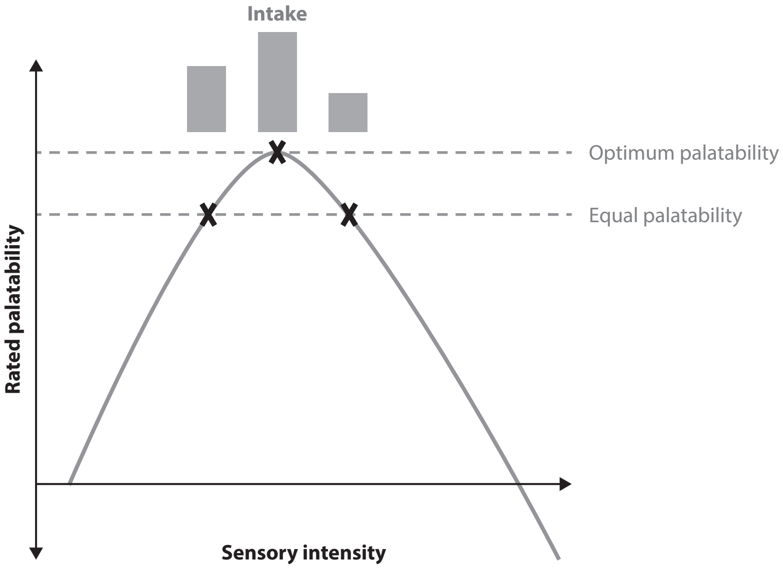

Figure 2

The proposed relationships among sensory intensity, rated palatability, and food intake. As perceived sensory intensity (e.g., taste intensity as a function of tastant concentration) increases, palatability increases to an optimum, after which further increases in intensity become less palatable. Intake tends to be lower at higher sensory intensity. Figure adapted from Reference 72 (CC BY-NC-ND 4.0).

suggesting that sensory intensity plays an important role in moderating intake beyond simply increasing palatability (11).

Higher sensory appeal is temporally linked to events that lead to the onset of satiation, such that higher liking may influence energy intake within a meal but have little or no impact on postmeal satiety (21). Evidence to date has provided no empirical basis for a distinct or elevated hedonic response to processed foods beyond established links between liking and energy intake. Conversely, extensive available evidence shows that increased exposure to a food's sensory properties during consumption tends to weaken rather than strengthen the hedonic valence of a stimulus, and food palatability naturally declines during consumption through a process known as sensory-specific satiety (SSS) (98). The onset of SSS is known to be delayed by increasing the variety of sensory cues experienced during consumption, but no study to date has demonstrated that SSS is interrupted or weakened by food processing or that it consistently differs between minimally and ultraprocessed foods. Conversely, limiting variety and promoting dietary monotony have been linked with lower consumption and are associated with a reduction in energy intake (17, 91).

Researchers have attempted to define what is meant by hyperpalatable by using dietary data to identify clusters of macronutrients most often associated with higher energy intakes (34). The implication is that excessive energy intakes are promoted by combinations of sweet, salt, and fat that override normal physiological regulation of energy intake. Note that a food's palatability (or liking) is a subjective, human affective response of an individual to the food's integrated sensory properties (95) that cannot be accurately predicted from its macronutrient composition or energy content. People differ widely in their liking for the same food, and a food's composition does not always reflect its sensory properties. For example, some solid foods can have sugar levels that are not reflected in their sweet taste intensity, while others may have a high salt content but may not be perceived as salty. The proposed definition of hyperpalatability suggests that all foods high in fat–sugar, fat–salt, or carbohydrate–sugar enhance palatability in a way that is greater than any of the key ingredients would produce alone (34), specifically, that such foods circumvent normal "physiological satiety mechanisms and activate brain reward neural circuitry" (34, p. 1762).

We note that there is no evidence that, on a calorie-for-calorie basis, processed foods have an elevated reward and a blunted satiety response. The only RCT to date that has compared satiety for unprocessed and ultraprocessed meals showed no significant difference in energy-adjusted scores for hunger, fullness, satisfaction, and capacity to eat (47). Brain imaging studies show that foods high in fat and carbohydrate are more "valued" in brain responses than foods containing either fat or carbohydrate alone (24). This has been described as a supra-normal response to formulations often found in many processed foods, where fats and carbohydrates may have a supra-additive effect on brain reward. These results are interesting and merit further research.

The link between brain reward circuitry and subsequent food intake is complex. To date, evidence from brain imaging has not demonstrated that a higher food reward from fat and carbohydrate mixtures predicts hyperphagic eating behavior and increased energy intake in controlled feeding trials. Moreover, incremental rises in a food's energy density do not necessarily result in higher palatability, food enjoyment, or an enhanced postmeal satisfaction that reduces later food intake (e.g., 104, 119).

Findings from controlled feeding studies may offer further suggestions on the mechanism by which combinations of high sugar, salt, and fat interact to increase both liking and energy intake. Researchers have explored the impact of taste intensity and fat on perception, liking, and intake for many years (25). Taste contributes significantly to palatability, whereas fat contributes much more to a food's energy density, with a relatively modest contribution to a food's sensory properties. On a gram-for-gram basis, fat contributes disproportionately to energy intakes as a result of its much higher energy density (i.e., 9 kcal/g versus 4 kcal/g for protein and carbohydrate). Researchers

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have mapped the psycho-hedonic functions of salt–fat mixtures (8), showing a 30% increase in energy intake when fat is consumed at an optimal salt intensity (7). The results show that optimal taste intensity drives liking, independent of fat content, whereas fat content has low taste activity but contributes much more to a food's energy density (8). The conclusion from these studies is that taste influences liking, whereas fat makes a disproportionately larger contribution to energy intake while having a much smaller direct effect on palatability (12). This may be the case with greater energy consumption from processed foods, which are often simultaneously high in both taste intensity and fat (e.g., fat–sugar and fat–salt/savory).

Unlike for taste, the ability to discriminate a food's fat content is a multisensory response that requires input from taste, texture, smell, and even visual cues (76). The covert manipulation of meal fat content is poorly detected or adjusted for, promoting what has been termed "fat hyperphagia" (e.g., 107). High fat content is relatively unpalatable on its own, but when combined with optimal taste intensities, it becomes acceptable (7, 8, 12). Foods that are high in fat often tend to also be high in salty, sweet, or savory taste (12, 33, 55, 129). At high taste intensities, our ability to discriminate between fat content becomes blunted, in what has been termed "fat blindness" (25–28). More broadly, recent findings suggest that our ability to discriminate foods according to their energy density decreases at high energy density, suggesting that humans are not well able to adjust intakes in response to highly energy dense foods (16). Humans can accurately and consistently discriminate between foods at energy densities up to an estimated cutoff of 1.75 kcal/g. However, above this estimated cutoff there is a tendency to underestimate successive increases in energy density as well as a rapid decrease in the ability to discriminate between high-energy-density foods (16). When we are not aware of high energy density, it becomes more difficult to adjust our portion selection or later energy intakes in response to consuming large amounts of energy-dense foods. This observation may help explain the sustained increases in energy intake observed in the RCT by Hall et al. (47), where the energy densities served were the same but the energy density consumed was significantly higher on the UPF diet, with negligible meal-to-meal adjustment for observed higher intakes within UPF meals.

Taken together, these findings suggest that high energy density, combined with higher eating rates, may promote overconsumption. At the population level, recent comparisons of dietary intakes within a Singaporean cohort highlight that the greatest differences in energy intake were attributable to greater intake of foods high in savory–fatty tastes (117) rather than neutral, sweet–sour, or sweet–fatty foods. Similar findings have been reported in the Netherlands (127) and Malaysia (118). Food formulation may therefore stimulate greater energy intakes in which at high taste intensity our ability to discriminate fat content (energy) becomes impaired.

Consuming high-energy-density foods is associated with greater energy intakes, and this association has been demonstrated across gender, weight class, age (adults and children), meal occasion, and macronutrient sources of energy (for a review, see 98). Research has also shown poor adjustment in later energy intake in response to higher (or lower) energy consumed within a test meal (4, 62, 72). This poor ability to adjust late intake has been widely demonstrated in studies that covertly add energy to or remove energy from meals and diets as well as in long-term studies that reduce dietary fat content and produce significant and sustained reductions in energy intakes (58, 63). As such, higher energy density and faster eating rates may combine to promote greater intakes when consuming highly processed foods (97).

Globally, the food industry is reformulating foods to reduce energy density, salt, sugar, and fat. These efforts have been made possible by advances in ingredient formulation and food processing and have created new opportunities for food producers to successfully reduce energy density while maintaining a food's sensory appeal. Both national and international programs are calling for calorie reduction targets, and significant progress in this area has been enabled by advances in

Table 1 Advantages and disadvantages of food processing and formulation

Advantages	Disadvantages
Improved microbial food safety	Thermal degradation of vitamins
Refining and milling to remove pesticides and other toxins (e.g., aflatoxin)	Excess public health–sensitive nutrients (salt, fat, and sugar)
Controlled processing and formulation to decrease toxin formation (e.g., acrylamide)	Increase availability of nutrient-poor (i.e., empty-calorie) foods that are high in energy density and easy to consume rapidly (i.e., higher kcal/min)
Inactivation of antinutritional factors	Separation technologies that remove nutrients (e.g., peeling)
Gelatinization of starches and denaturation of proteins to increase digestibility	Formulations that could increase consumption rates of high-energy foods (energy-dense liquids, softer solids, semisolids)
Low-temperature and/or short-time processing and rapid freezing to optimize vitamin retention	
Fortification of foods for widespread nutrient delivery	
Obtaining raw materials at scale to decrease food prices	
Conversion of processing waste streams into new products to decrease food prices and decrease waste	
More energy-efficient processing equipment to increase sustainability	
Use of processing, additives, and packaging to increase shelf-life and decrease food waste	
Use of continuous processing operations to decrease water use	

food formulation and processing. While evidence from research shows that higher energy density can promote excessive calorie consumption, future research is needed to establish whether sensory cues and reductions in energy density can support sustained reductions in dietary energy intake and help consumers to maintain food intake patterns that keep a food's sensory appeal while reducing the risks associated with overconsumption.

5. CONCLUSIONS

Consumer food purchases are driven by taste, value, convenience, nutrition, and sustainability. As our lifestyles have changed, we have been able to spend less money on food and less time on shopping and cooking. Food processing and formulation have both advantages and disadvantages (**Table 1**), though current recommendations to remove all UPFs from the diet seem regressive and unrealistic (79, 80). Taxing foods by their degree of processing is likely to disproportionately affect the most vulnerable and food-insecure consumers and targeting food palatability seems unlikely to be successful with food producers or consumers. As such, making our food supply more expensive and less appealing is unlikely to become the basis for public health policy (77). Reverting to cooking all of our foods from scratch will be difficult, if not impossible, for many. In addition, many lower-income populations will have difficulty adjusting to diets that require them to spend more of their disposable income on food and a greater proportion of free time on food preparation. Thus, while some sectors of the population might be able to reduce the proportion of processed foods in their diet, for most consumers it will be difficult or impossible to do so and still meet their daily nutrient requirements (48). It is important to reformulate certain elements of the current food supply to ensure that foods remain appealing and convenient but also have the appropriate nutrient density for different populations. Improving rather than removing processed

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foods is likely to be a more practical way to enhance the healthfulness and sustainability of the modern food supply (121).

Food processing in factories, in food service, and at home is important because it makes foods safe and increases digestibility, nutrient bioavailability, palatability, and shelf-life. Industrial food processing has the additional benefit of economies of scale, which decreases food costs, utilizes food by-products, reduces production energy, and utilizes food additives and packaging technologies to further extend shelf-life, resulting in less food waste and more sustainable food production. Food processing technologies and formulation can also help increase the acceptability, convenience, and cost of sustainable plant-based substitutes for animal-based foods. Recommendations to avoid all processed food should take into account the significant environmental impact of such a global shift. Because of its size, the food industry will be essential in any effort to reduce the environmental impact of food preparation, and in the future, food processing, formulation, and technological innovation will be necessary for the development of new foods and food categories that can help consumers shift toward more sustainable food sources.

Classification schemes such as NOVA imply that food processing operations affect food-related health outcomes, but these relationships have not been directly established. Instead, it seems more likely that what is already known about nutrients that have traditionally been the subject of public health concern (e.g., salt, sugar, and fat) has a greater impact on health outcomes. As a result, researchers are focusing their efforts on these nutrients to reformulate and improve the food supply. A historical example of this concept is food fortification, which provides affordable access to nutrients to billions of people around the world who might otherwise struggle to meet their nutritional requirements. However, according to NOVA, any attempt to reformulate or fortify a food or beverage can only make it even more processed and unhealthy (100). Such attempts include food fortification to enhance micronutrient content, sugar reduction supported by nonnutritive sweeteners, removal of fat from dairy products, creation of breast-milk substitutes to support infant growth, addition of pre- and probiotic cultures to improve gut health, and technological advances that support efforts to make food production more sustainable. Thus, in the current environment, manufacturers and consumers are challenged to either avoid UPFs entirely or embrace reformulation and processing as an approach to reduce public health–sensitive nutrients and boost the nutrient density and sustainability of the food supply.

Many food manufacturers attract consumers by creating sensory properties that meet the greatest driver of food purchases: taste. Efforts to improve the food supply still require this approach, for instance, in the development of novel processed foods that facilitate the reduction or removal of public health–sensitive nutrients such as salt, sugar, and fat, or for foods that are unlikely to be consumed on a regular basis. This global drive to improve public health has stimulated national and international commitments to reformulation targets; public–private partnerships to collectively reduce the calorie content of many processed foods and snacks, such as the Healthy Weight Commitment Foundation Initiative (84); and government actions, such as Public Health England's calorie reduction targets for sweet and savory discretionary calories (90, 111).

If we accept that food processing and formulation are part of the current public health problem, then we must also accept that reformulation and improvements in food processing will be central to any effort to reduce the energy density, improve the nutrient density, and enhance the sustainability of the food supply (121). However, attempts to simply reformulate foods to decrease sugar, salt, and saturated fat will help overcome these serious public health challenges only if the new formulations sustain sensory appeal and positively affect eating behaviors. Beyond food formulation, food sensory cues such as form and texture influence eating behaviors and energy intakes. Future research should consider the important role of sensory cues in moderating food choice and intake behaviors and the interaction between a food's sensory and nutritive properties to align the food's

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appeal with an individual's eating behavior and nutrient needs. Thus, the challenge ahead will be to apply the latest innovations in food processing and formulation not only to decrease negative nutrient content but also to consider foods' sensory properties to moderate energy intake and make them desirable to consumers, so that these foods become part of the daily diet.

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Annual Review of
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Volume 42, 2022

Contents

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