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Review

Revisiting the Ultra-Processed Food Concept: A Critical Review of Its Scientific Basis and Implications for Food Classification

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Abstract

The NOVA classification groups foods according to the extent and purpose of industrial processing, and observational studies have associated high consumption of ultra-processed foods (UPFs) with adverse health outcomes. Whether the degree of processing alone is a sufficient criterion for assessing food quality, however, remains under debate, since observational associations do not by themselves identify processing as the causal factor. This review critically examines the conceptual basis of the UPF category and the relationships among food processing, formulation, nutritional quality, and health. Processing can have beneficial or detrimental effects depending on the technology, formulation, and food matrix involved: it may improve safety, shelf life, digestibility, bioavailability, and sustainability, but may also reduce the content or functionality of sensitive nutrients and bioactive compounds. Examples from reformulation, functional foods, clean-label development, sugar replacement, and innovative technologies illustrate these interactions. Nutrient Profiling Models, the Nutrient-Rich Food Index, the Food Naturalness Index, and dietary inflammatory indices are discussed as complementary approaches with their own limitations. We conclude that food quality is unlikely to be captured by the degree of processing alone and that future classification systems should integrate nutritional quality, food matrix, formulation, processing, health outcomes, and sustainability.

Keywords: ultra-processed food; nutritional value; food labelling; functional food; food formulation; environmental impact of foods

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1. Introduction

The increasing prevalence of obesity and metabolic disorders has placed nutrition at the center of global efforts to prevent non-communicable diseases (NCDs). Although these conditions arise from complex interactions among biological, behavioral, environmental, and socioeconomic factors, diet remains one of the most modifiable determinants of population health [1,2]. Traditionally, foods have been evaluated mainly according to their nutrient composition, with nutritional quality inferred from the amounts of energy, macronutrients, micronutrients, and other biologically relevant components they provide [3]. Over the last decade, however, increasing attention has shifted toward another characteristic of foods: the extent and nature of their processing [4].

This change in perspective has been strongly influenced by the NOVA classification, which introduced the category of ultra-processed foods (UPFs) and organized foods according to their degree and purpose of processing [5]. Unlike nutrient-based systems, which require an interpretation of nutritional composition, NOVA offers an intuitive way to distinguish foods based on how they are produced. This simplicity has made this framework particularly appealing for epidemiological research—where broad food categories must be applied consistently to large populations—and for public communication [6]. Consequently, the concept of UPFs has transcended the boundaries of nutritional research, garnering the attention of organizations such as the World Health Organization (WHO) and the Food and Agriculture Organization of the United Nations (FAO) in discussions about healthy and sustainable diets [3,7].

Observational evidence supports the relevance of this approach for public health. Umbrella reviews of meta-analyses and large prospective cohorts have reported associations between higher UPF consumption and a greater risk of obesity, type 2 diabetes, cardiovascular disease and all-cause mortality [8,9], and an inpatient randomized trial showed higher energy intake and weight gain with an ultra-processed diet than with a minimally processed one [10]. NOVA has also proved practical for epidemiological studies, where simple categories can be applied consistently to large datasets, and it has informed dietary guidelines in several countries. However, the certainty of the evidence varies between outcomes, most studies are observational, and diets high in UPFs typically differ from other diets in several respects, such as energy density, sugar, saturated fat, sodium and fibre [8,11].

However, a classification system used to inform dietary recommendations worldwide must not only be useful from an epidemiological standpoint but also consistent with established knowledge in food science. A fundamental challenge arises from interpreting epidemiological associations between UPF consumption and adverse health outcomes as evidence that processing itself is the causal factor, since observational designs cannot easily separate the effect of processing from that of nutrient composition, dietary pattern and socioeconomic context [6]. Foods classified as UPFs can differ substantially in their ingredient composition, nutritional density, structural matrix, and technological purpose [12]. Treating processing as a general indicator of healthfulness can, therefore, obscure the specific biological and chemical properties of foods that actually influence human health [13].

Furthermore, the negative connotation increasingly associated with food processing overlooks its indispensable role in modern food systems. Processing is essential for ensuring food safety, preserving perishable raw materials, extending shelf life, and making food available on a scale compatible with a growing global population [13,14]. Therefore, the relevant scientific question is not simply whether a food has been processed, but rather which specific processes have been applied, how they interact with the food's formulation, and what consequences they have for the final product [6,12].

Consequently, the primary objective of this review is to critically examine the scientific basis and limitations of the concept of ultra-processed foods within the NOVA classification. Specifically, we analyze the necessary distinction between food formulation and food processing, evaluate how technological interventions influence both nutritional quality and sustainability, and consider alternative quantitative approaches, such as the Nutrient-Rich Food (NRF) Index and the Food Naturalness Index (FNI), that may provide more robust, evidence-based criteria for food classification. Unlike recent reviews that focus mainly on the epidemiological evidence or on NOVA as a classification tool, this review adopts a food science and technology perspective: it distinguishes formulation from processing, uses specific technologies (drying, enzymatic treatments, microencapsulation) to illustrate the heterogeneity within NOVA categories, and discusses compositional and naturalness

indices together with environmental considerations. We do not dispute the epidemiological associations; rather, we examine what the UPF category can and cannot tell us about the properties of individual foods.

2. Healthy Food and Healthy Diet

Although a broad scientific consensus defines a healthy diet as a balanced intake of diverse, nutrient-rich foods—such as fruits, vegetables, whole grains, legumes, and nuts—that supply adequate energy and nutrients to support physiological functions [3,14,15], a universally accepted formal definition for individual "healthy foods" remains elusive. For instance, in 2016, the U.S. Food and Drug Administration (FDA) established criteria allowing the "healthy" claim on food products if they are either predominantly rich in mono- and polyunsaturated fats (regardless of total fat content) or provide at least 10% of the Daily Value (DV) for potassium or vitamin D [16]. However, such regulatory guidelines are often imprecise and inconclusive, potentially leading to consumer misinterpretation.

The inherent compositional variability of natural foods further complicates their classification. Fruits and vegetables are primary sources of carbohydrates, dietary fiber, and minor bioactive compounds (e.g., antioxidants, pigments, and vitamins), yet they possess negligible lipid and protein contents. Conversely, other foods, such as certain nuts and seeds, are highly energy-dense due to their elevated fat content. While many public health guidelines and nutritional labels focus heavily on restricting saturated fats, it is imperative to recognize that all lipids, regardless of their health profile, provide 9 kcal per gram. Furthermore, fatty acid chain length dictates metabolic behavior; for example, short-chain saturated fatty acids elicit physiological responses distinct from those of long-chain saturated fatty acids [17]. Additionally, nutrient-dense natural foods of animal origin inherently lack dietary fiber and specific antioxidants. Consequently, evaluating whether a specific food matrix is beneficial must be grounded in a rigorous, comprehensive nutritional profile rather than the isolated presence or absence of specific macronutrients.

Evaluating dietary healthfulness therefore extends beyond single-food analysis and requires addressing complex nutritional and environmental variables. A comprehensive assessment must consider the overall balance of macro- and micronutrients, the synergistic interactions between different foods, and the extent to which the structural food matrix modulates nutrient bioavailability [18]. Furthermore, modern dietary paradigms must integrate the environmental impact across the food value chain and account for the confounding effects of lifestyle factors, such as sedentary behavior, sleep quality, and psychological stress. In this multifactorial context, framing food processing as the sole or primary driver of poor health outcomes oversimplifies the issue. Rather than penalizing technological interventions, the scientific community must prioritize establishing rigorous, composition-based definitions for nutritionally unbalanced foods to better inform public health strategies.

3. Ultra-Processed Food

The NOVA classification system categorizes foods into four groups: (1) unprocessed or minimally processed foods, (2) processed culinary ingredients, (3) processed foods, and (4) ultra-processed foods (UPFs) [12]. Unlike traditional nutrient-based classification approaches, the NOVA framework represents a fundamental shift by categorizing foods based on the extent and purpose of their processing [6]. However, critics have increasingly argued that this system lacks a robust grounding in established scientific evidence and departs from recognized nutritional principles [13] (Figure 1).

According to the NOVA framework, UPFs are broadly defined as formulations of ingredients—mostly for exclusive industrial use—created through a series of industrial

processes requiring sophisticated equipment and technology [12]. From a food science perspective, this definition presents several inconsistencies and ambiguities.

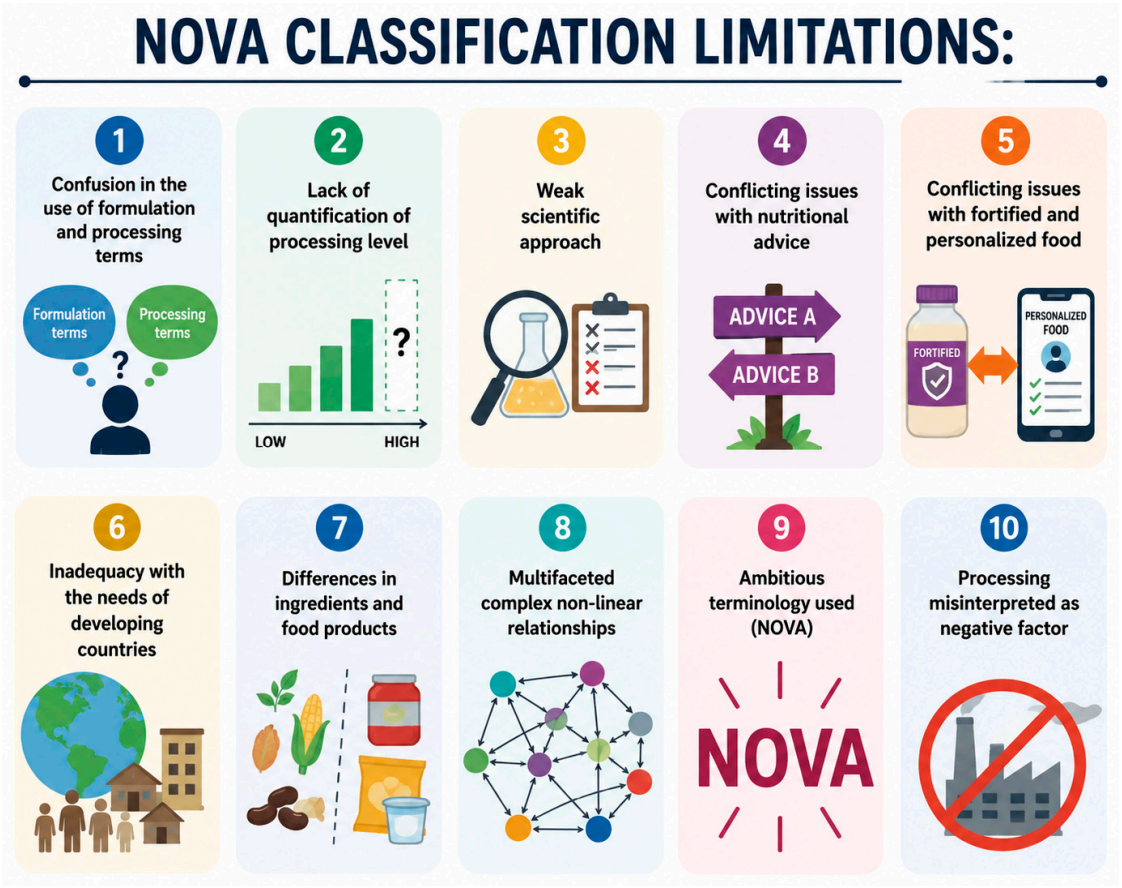


Figure 1. Main limitations of the NOVA classification.

Mischaracterization of Industrial Ingredients: The assertion that "ingredients of exclusive industrial use" are inherently detrimental is scientifically imprecise. Numerous industrially utilized ingredients, such as pectins, oligosaccharides, dietary fibers, omega-3 fatty acids, phytosterols, vitamins, and phenolic compounds, are explicitly added to improve human health. Furthermore, incorporating ingredients recovered from agri-food by-products promotes a circular economy and enhances environmental sustainability within contemporary food systems [14,19]. If novel manufacturing procedures substantially modify these bioactive ingredients, they are already subject to rigorous, independent safety evaluations by regulatory bodies such as the European Food Safety Authority (EFSA) [20].

Contradictions in the Degree of Processing: The NOVA framework assumes that "sophisticated equipment" is indicative of UPFs. Yet, technologies that can negatively impact nutritional quality, such as pasteurization (which can denature proteins or degrade bioactive compounds), belong to NOVA Category 1 (unprocessed/minimally processed foods) [21]. Conversely, the framework does not distinguish among enzymatic treatments: those used to improve the digestibility or bioavailability of nutrients in an otherwise intact food matrix and those used to fractionate and reconstitute food components may be grouped together under the UPF definition [22]. Moreover, not every enzymatic modification (e.g., cross-linking) necessarily improves nutritional value, so these cases need to be assessed individually.

Overlap with Functional Foods: A more extensive NOVA definition characterizes UPFs by the fractionation of whole foods, chemical modifications (e.g., hydrolysis, hydrogenation), and the addition of colors, flavors, and emulsifiers [12]. However, these exact technological stages are frequently required in the development of functional foods prod-

ucts deliberately formulated to provide health benefits beyond basic nutrition [23]. This overlap can easily mislead consumers and generate unwarranted public health concerns regarding beneficial products [5]. It should be noted, however, that some functional foods are also high in sugar or fat, and that hydrolysis, hydrogenation (partial hydrogenation may generate trans fatty acids) or the addition of additives does not in itself imply a health benefit. The nutritional value of each product must therefore be assessed individually, on the basis of its composition and of the evidence supporting its claimed effects.

Several mechanisms have been proposed to explain the associations between UPF consumption and adverse outcomes, including high energy density, fast eating rate favoured by soft textures, hyperpalatability, unfavourable nutrient composition (high in free sugars, saturated fat and sodium; low in fibre and protein), disruption of the food matrix, and displacement of minimally processed foods from the diet [24–26]. Some of these factors, such as nutrient composition and energy density, are determined mainly by formulation, whereas others, such as texture and matrix disruption, result from the interaction between formulation and processing. Because these characteristics are not exclusive to processed foods and vary widely among UPFs, the degree of processing alone is an incomplete criterion of healthfulness, and terms such as "nutritionally unbalanced foods" may describe more precisely the products for which energy density and a poor nutrient profile are the underlying concern [14,27].

The NOVA framework does not state that every UPFs is unhealthy, and epidemiological studies assess the proportion of UPFs in the whole diet rather than individual products. At the product level, however, the category groups foods of markedly different nutritional quality. Everyday items such as packaged wholegrain breads, yogurts, fortified plant-based milk alternatives, and baked beans are classified as UPFs, despite providing essential nutrients (e.g., protein, fibre, iron, and potassium) that contribute to disease prevention and metabolic stability [25]. A sugar-sweetened cola and a fortified unsweetened soy drink, or a cream-filled biscuit and a packaged wholegrain bread, all belong to NOVA group 4 yet differ greatly in sugar, fibre, protein and micronutrient content. The UPF label is therefore informative at the level of dietary patterns, but has limited value for guiding choices among individual products [28].

Assessing the health impact of food requires a nuanced approach that distinguishes between formulations with demonstrated health benefits and those that pose risks. When products with healthy nutritional profiles are excluded from the UPF category, over 80% of the remaining items meet the definition of foods high in fat, salt or sugar (HFSS) [28]. HFSS and NOVA capture different attributes: HFSS is based exclusively on nutrient composition, whereas NOVA considers the purpose and extent of processing, the ingredients and the use of additives. The two systems overlap in products such as confectionery, sugar-sweetened beverages and many snacks, but diverge in others: packaged wholegrain bread or unsweetened fortified plant-based drinks may be NOVA 4 without being HFSS, while some traditional or home-made products rich in sugar or fat are HFSS without being NOVA 4. Because HFSS can be calculated from nutrient composition data, it can be applied more transparently and reproducibly [29], whereas assigning foods to NOVA groups in dietary surveys often requires assumptions about preparation methods and ingredients. For example, in a detailed classification of the UK National Diet and Nutrition Survey, fresh foods that were boiled or grilled were assumed to belong to NOVA group 1 when the item name did not specify added salt or fat [30]. HFSS, however, does not capture additives, food matrix or processing effects, so it should be regarded as complementary to, rather than a replacement for, other approaches [31].

4. The Impact of Food Processing Techniques

The extent and type of processing profoundly influence the final nutritional and physicochemical properties of food. Consequently, relying solely on the degree of processing (as the NOVA classification does) is insufficient for an objective evaluation of food quality. A comprehensive classification system must incorporate quantitative metrics for nutritional value, nutrient bioaccessibility, digestibility, sensory attributes, shelf-life, and environmental sustainability.

4.1. Variability Within Minimal Processing: The Case of Drying

To illustrate the limitations of process-based categorization, consider drying, a technique permitted within NOVA Category 1 (unprocessed or minimally processed foods). Drying induces significant physical, chemical, and nutritional transformations within the food matrix [32]. Key quality attributes such as color, aroma, texture, rehydration capacity, bulk density, flowability, water activity, and the retention of nutrients and volatile compounds are substantially altered during this process [33,34]. From a nutritional perspective, exposure to elevated temperatures, oxygen, and cellular disruption accelerates the degradation of bioactive compounds. For instance, phenolic compounds are highly susceptible to enzymatic degradation via polyphenol oxidase, while the highly unsaturated structures of carotenoids make them vulnerable to autocatalytic oxidative and thermal degradation [35]. The retention of these sensitive compounds, alongside vitamin C, which frequently serves as a primary indicator of overall nutrient preservation due to its high thermolability [36], is heavily dependent on specific processing parameters, such as temperature and initial moisture content. Although most of the heat-sensitive compounds discussed here are of plant origin, processing also affects animal-derived components, such as long-chain omega-3 fatty acids in fish, which are prone to oxidation during thermal treatment, and available lysine in dairy and meat products, which can be lost through Maillard reactions [37]. Numerous comprehensive reviews highlight how varying drying conditions dictate functional and nutritional preservation [38].

Conversely, freeze-drying represents a highly effective dehydration method for plant-based foods. The absence of liquid water, an oxygen-limited vacuum environment, and low operational temperatures effectively mitigate compound degradation. Although associated with higher operational costs and longer processing times, freeze-drying ensures superior retention of nutritional and functional components compared to conventional thermal methods [32]. However, freeze-drying has a high energy demand and cost, which limits its use in mass food supply chains [34]; the comparison is used here only to illustrate the heterogeneity within a category, not to recommend a particular technology.

This contrast suggests that a single “minimal” processing category can encompass techniques that either degrade or preserve nutritional value to very different extents, which limits the discriminating power of broad processing categories.

4.2. Consumer Perception vs. Technological Reality

While governments and international organizations increasingly advocate for healthier and more sustainable food systems, consumer perception often equates processing with diminished healthfulness and naturalness [39]. For example, many fresh fruits and vegetables undergo essential postharvest preservation treatments (such as controlled or modified atmosphere storage, edible coatings, and ultraviolet (UV) irradiation) to maintain quality and extend shelf-life before reaching the market [40]. Because consumers are largely unaware of these practices, food scientists face the complex challenge of balancing actual product quality, sustainability, and subjective consumer perceptions of naturalness [13]. Limited consumer awareness of these practices is not in itself an argument against a classification

system; rather, it highlights the need for transparent communication of the treatments actually applied to foods.

4.3. Disentangling Formulation and Processing

To establish scientifically grounded definitions of food quality, formulation and processing must be evaluated as distinct determinants. Formulation involves the systematic selection and proportioning of ingredients, whereas processing constitutes the physical or chemical treatments applied to achieve specific outcomes. These two variables act synergistically or antagonistically to shape a product's nutritional value, safety, palatability, and sustainability. The NOVA system currently fails to account for functional relationships across digestive and metabolic pathways. Processing can actively enhance nutrient functionality; for example, partial protein denaturation improves digestibility. Furthermore, the food matrix modified during processing governs the release kinetics of embedded nutrients, subsequently optimizing their bioaccessibility and bioavailability throughout the digestive tract. Because the nutritional composition is inherently shaped by formulation and further modified by technological methods, F and P should be integrated as separate, quantifiable criteria in future food classification systems [27]. This interdependent approach is essential for driving food innovation within the framework of a circular economy and designing foods optimized for sustainable nutrition [41,42].

These distinctions can be illustrated with examples. A processing effect is exemplified by the thermal treatment of tomato, which increases the bioaccessibility of lycopene; a formulation effect, by sodium reduction or fibre fortification of a bakery product; and a matrix effect, by the different digestion kinetics and energy availability of whole versus milled nuts or cereals [42,43]. Because NOVA assigns a single category on the basis of the combination of these factors, it cannot separate their individual contributions.

5. Food Formulation and Reformulation Strategies

Food formulation is a fundamental component of product development that determines the structural composition, energy density, and nutrient profile of a food matrix through the precise combination of ingredients. Alongside processing techniques, formulation is designed to achieve specific nutritional objectives while ensuring essential quality attributes such as safety, stability, and shelf life. Furthermore, it governs sensory characteristics, including appearance, aroma, flavor, taste, and texture, which are critical determinants of consumer acceptance and purchasing behavior [44]. Formulation must also integrate commercial and environmental considerations, encompassing production costs, regulatory compliance, and sustainability metrics.

To mitigate the adverse health effects associated with excessive caloric and sodium intake, food reformulation efforts have predominantly focused on reducing or replacing added sugars, salt, and saturated fats [45]. Extensive research has explored healthier alternatives for these components [46]. However, substituting sugars, salt, and saturated fats presents significant technical challenges because these ingredients dictate essential structural properties, processing functionality, and shelf life [47]. Consequently, reformulation frequently alters taste and texture profiles, increases production costs, and diminishes consumer acceptance. To maximize public health benefits, nutrient reduction strategies should target specific food categories where they can yield the most substantial impact. For example, substituting sodium chloride with potassium-based salts has emerged as an effective intervention to reduce dietary sodium while delivering measurable health improvements [48].

Beyond nutrient reduction, formulation strategies actively enhance nutritional quality through the fortification of products with proteins, dietary fibers, vitamins, and essential

minerals to address the specific needs of diverse population groups. Advanced formulation techniques, such as microencapsulation, are highly effective for protecting sensitive bioactive compounds and functional ingredients. Various microencapsulation methodologies, including spray drying, freeze-drying, fluidized bed coating, extrusion, supercritical fluid processing, and electrospinning, significantly improve compound stability, enable controlled release kinetics, and maximize bioavailability within food applications [14].

In the context of bakery products such as cookies and cakes, sugar represents a major structural ingredient that typically accounts for 30 to 40 percent of the total formulation. Growing public health concerns regarding excessive energy intake have catalyzed extensive research into low-calorie sugar alternatives. Nevertheless, replacing sugar in bakery and confectionery systems remains inherently difficult because sucrose fulfills multiple technological functions beyond imparting sweetness. It fundamentally contributes to the structural integrity, texture, stability, and overall sensory quality of the final product. Therefore, developing a successful sugar replacement strategy requires a comprehensive understanding of the specific functional roles that sucrose plays within a given food matrix. These complex interactions can be systematically evaluated using qualitative and semiquantitative analytical frameworks, such as the Complex Dispersed System (CDS) methodology [49,50].

6. Nutritional Quality Indexes

Alternatively, policies and dietary guidelines targeting UPFs can be developed based on objective nutrient profiling and food groups to encourage healthier dietary patterns among populations. To assist in food classification, several nutrient density and nutrient profiling models have been established [27,51,52]. For the precise quantification of nutritional value, the well-established NRF Index provides a formulation-based metric. The NRF characterizes the nutritional profile of food products by evaluating two distinct categories of nutrients, which are recommended nutrients and nutrients to limit (LIMs) [53,54]. A prominent application of these frameworks is the Nutrient Profiling Model (NPM) [55], which is utilized to identify foods classified as HFSS and serves as the basis for several public health policies [28]. The NPM employs an objective algorithm involving three sequential steps. First, 'A' points are assigned based on the levels of energy, saturated fat, total sugars, and sodium. Second, 'C' points are allocated for beneficial components, including dietary fiber, protein, and the proportion of fruits, vegetables, and nuts. Finally, the total 'C' points are subtracted from the 'A' points to generate a final score. Foods scoring 4 or higher and beverages scoring 1 or higher are designated as HFSS and considered less healthy, while products falling below these thresholds are considered non-HFSS. By balancing beneficial nutrients against those associated with metabolic risk, this compositional approach provides a transparent, nutrient-based rationale that complements processing-based classifications [56]. However, a limitation of these nutritional indexes is the type and extent of processing is not incorporated. Hence, it has been recently recommended that nutrient profiling and front-of-pack labels evolve to address processing effects [57–59].

Beyond nutrient composition, the FNI introduced by Sanchez-Siles et al. [29] provides a comprehensive framework designed to objectively assess the naturalness of food products. Based on naturalness attributes prioritized by consumers alongside regulatory and technical considerations, the FNI evaluates four specific dimensions: farming practices, absence of additives, absence of unexpected ingredients, and degree of processing. These components yield a score ranging from 1 for the lowest naturalness to 5 for the highest naturalness [60]. Unlike studies relying on subjective consumer perceptions, the FNI utilizes verifiable label information and correlates strongly with consumer evaluations across a broad range of products [29,61,62].

Crucially, the application of this index suggests that the degree of food processing does not necessarily correlate with healthiness or naturalness. For example, an analysis of 734 snack bars all classified as UPFs under the NOVA framework revealed substantial variation in both nutritional quality and naturalness. Products ranged from healthy and natural to unhealthy and unnatural. Fruit-based bars frequently achieved high ratings for both nutritional qualities measured by Nutri-Score and naturalness measured by FNI, whereas cereal bars generally received lower scores. These findings highlight the limited ability of the NOVA classification to adequately differentiate foods based on their actual nutritional and functional value [6,13,56].

Finally, the dietary inflammatory index (DII) represents another valuable metric for determining the physiological impact of foods. The DII was developed through a comprehensive literature review examining associations between specific dietary parameters and six inflammatory biomarkers. Dietary components were classified according to their reported effects as anti-inflammatory (-1), neutral (0), or pro-inflammatory $(+1)$, with scores subsequently weighted based on the hierarchy of scientific evidence. The final score for each parameter is calculated by dividing the weighted difference between anti-inflammatory and pro-inflammatory evidence by the total weighted evidence, followed by an adjustment to account for the overall robustness of the available literature [63].

These tools measure different constructs and are not interchangeable. The Nutrient Profiling Model and the NRF Index are based on nutrient composition and do not consider processing, additives or food matrix; both depend on the choice of nutrients, thresholds and reference amounts, and the Nutrient Profiling Model was developed for specific regulatory uses. The FNI is based on label information and consumer-relevant naturalness attributes, but it is not a measure of nutritional or health value and its validation against health outcomes is limited. The DII was developed to characterize the inflammatory potential of overall diets and relies on literature-derived scores, so its application to individual foods is limited. As a consequence, the same product may be ranked differently by different tools, and head-to-head comparisons against health outcomes are still scarce. Table 1 summarizes the main characteristics of these tools, including NOVA, to facilitate their comparison.

Table 1. Comparison of NOVA, the Nutrient Profiling Model (HFSS), the NRF Index, the Food Naturalness Index and the Dietary Inflammatory Index [27,29,53–55,63].

Tool	Classification Basis	Intended Purpose	Main Strengths	Main Limitations	Validation/ Applicability
NOVA	Purpose and extent of industrial processing; ingredients and additives	Epidemiological research; dietary guidelines	Simple categories; applicable to large datasets; consistent associations with outcomes in cohorts	Heterogeneity within group 4; does not measure nutrient content; does not separate formulation from processing; classification depends on assumptions	Widely used in cohort studies; reproducibility of classification varies
Nutrient Profiling Model (HFSS)	Nutrient composition (points for energy, saturated fat, sugars, sodium vs. fibre, protein, fruit/ vegetables/nuts)	Regulation of marketing and promotion of HFSS foods	Objective; based on label data; reproducible	Ignores processing, additives and matrix; binary threshold; developed for specific policy uses	Developed for regulatory use; requires adaptation for other contexts

Table 1. *Cont.*

Tool	Classification Basis	Intended Purpose	Main Strengths	Main Limitations	Validation/ Applicability
NRF Index	Balance between nutrients to encourage and nutrients to limit	Ranking of nutrient density	Quantitative; flexible	Results depend on selected nutrients, reference amounts and basis (per 100 kcal or serving); ignores processing and matrix	Compared with diet quality measures in several studies
Food Naturalness Index (FNI)	Label information on farming practices, additives, unexpected ingredients and degree of processing (1–5)	Assessment of naturalness of products	Verifiable from labels; correlates with consumer perception	Not a measure of nutritional or health value	Limited validation against health outcomes
Dietary Inflammatory Index (DII)	Literature-derived inflammatory effect scores of dietary parameters	Inflammatory potential of overall diets	Linked to inflammatory biomarkers	Developed for diets rather than single foods; depends on intake data and literature; captures only inflammation	Mainly applied in epidemiological studies of diets

7. Consumer Demand for Clean-Label Foods and Natural Functional Ingredients

The rising consumer preference for clean-label foods, primarily motivated by an aversion to synthetic additives, has prompted the food industry to minimize the use of artificial ingredients. Nevertheless, these compounds perform essential technological functions, including ensuring product stability, microbiological safety, extended shelf life, and sensory acceptability. The necessity of these additives is particularly pronounced in reformulated matrices, such as plant-based meat alternatives and gluten-free products, where they compensate for the structural and functional deficits of alternative ingredients [64].

Consequently, a major challenge in modern food science lies in identifying naturally derived, multifunctional ingredients capable of replicating the performance of conventional synthetic additives without compromising process compatibility or final product quality. Substituting multiple synthetic compounds with a select number of natural alternatives effectively simplifies ingredient lists and aligns with clean-label paradigms.

While this market-driven shift stimulates continuous research into novel ingredients and innovative processing technologies, claims regarding their health and environmental benefits must be substantiated by rigorous scientific validation. In this context, advanced analytical frameworks, particularly foodomics, provide a comprehensive systems-level perspective. These methodologies enable researchers to evaluate the complex interactions between food composition, technological processing, and their subsequent effects on the human metabolome, thereby bridging the gap between clean-label formulation and evidence-based health outcomes [41].

8. Environmental Impact of Foods and Circular Economy

Integrating valorized agro-industrial by-products into food formulations represents a critical strategy for minimizing environmental impact and advancing circular economy principles. Given that approximately one-third of global food production is lost or wasted, recovering valuable nutrients from residual biomass offers a dual benefit of reducing environmental pressure and addressing population-wide nutrient deficiencies. For example, in addition to cereal-derived bran and germ, residues from fruit and vegetable processing

are increasingly utilized to replace refined or synthetic ingredients. Martins et al. [65] comprehensively reviewed the potential of fruit by-products, highlighting how their nutrient profiles, bioactive compounds, and rheological properties can significantly improve the technological and sensory characteristics of bakery products.

However, the direct incorporation of alternative flours, dietary fibers, seeds, or whole-wheat ingredients presents substantial technological challenges. These additions frequently disrupt the starch and gluten matrix and alter dough viscoelasticity, which can compromise the final sensory quality and structure of products such as bread [66]. Furthermore, most raw residual biomass does not inherently meet food-grade safety and nutritional standards. Nutritional suitability requires the strict absence of antinutritional compounds, an accessible structural matrix, and high macro- and micronutrient bioavailability. Because agricultural residues often exhibit compositional heterogeneity, contain biological antinutrients, and possess recalcitrant structural matrices, they severely limit direct edibility and nutrient accessibility.

Consequently, targeted food processing is strictly necessary to convert these raw residues into safe and functional ingredients. Processing steps are required to disrupt physical barriers, eliminate undesirable compounds, and increase the concentration and bioavailability of valuable nutrients. By utilizing innovative food technologies, multiple synthetic additives can be replaced with a smaller number of natural and structured ingredients derived from these by-products. This approach can effectively shift certain products away from the ultra-processed designation toward clean-label formulations while simultaneously improving product stability and shelf life. Ultimately, successfully developing these sustainable foods without compromising nutritional quality requires close collaboration between food technologists and nutritionists, ensuring that public health and environmental objectives are met synergistically [41].

9. Functional Foods

Current industry efforts to develop healthier products predominantly focus on reformulating existing foods to lower energy density, reduce salt, sugar, and fat content, and incorporate high-fiber or gluten-free alternatives [67]. Despite these nutritional improvements, many commercially available reformulated products fail to replicate the complex taste and texture of their conventional counterparts, which significantly limits consumer appeal and market acceptance [59].

Within this context, classifying foods strictly according to their degree of processing rather than their compositional quality is highly problematic. This processing-centric approach can lead consumers to perceive all ultra-processed foods negatively, completely disregarding their actual nutritional value or clinically substantiated health claims [56]. It is imperative to recognize that extensively processed functional foods are not inherently detrimental to human health. On the contrary, these products are explicitly formulated to improve physiological biomarkers and mitigate the risk of non-communicable diseases. Through meticulous formulation and scientific validation, manufacturers integrate targeted nutrients, bioactive compounds, and functional ingredients into the food matrix to deliver specific health benefits [68]. Therefore, even if a functional product is categorized as an UPF under the NOVA system, its true health impact must be evaluated based on its specific nutritional profile and the rigorous scientific evidence supporting its efficacy [69].

10. Future Perspectives and Methodological Innovations

10.1. Predictive Machine Learning and Machine Vision Systems

Predicting nutrient transformations during processing remains highly challenging due to the inherent chemical and structural complexity of the food matrix [59,70]. The

lack of complete mechanistic understanding regarding the reactions occurring within these systems often limits the development of traditional prediction models. Predictive machine learning (ML) models provide a robust, data-driven alternative to overcome these limitations. By leveraging experimental data across diverse food types and cooking methods, ML algorithms can identify complex patterns in large datasets, thereby enabling the accurate prediction of nutrient transformations even when underlying mechanisms are not fully elucidated [71].

For example, alternative machine learning frameworks have been successfully developed to predict the micronutrient composition of processed foods based on the nutrient profiles of their raw counterparts. These studies highlight the critical importance of appropriate data scaling and transformation prior to model training to mitigate biases associated with processing yield variations. Ultimately, these advanced predictive techniques offer significant advantages over conventional methods and provide essential recommendations for standardizing food composition databases, improving data quality assurance, and optimizing sampling strategies [72]. Nevertheless, these approaches depend on high-quality, representative and well-labelled datasets, and food composition data remain scarce in many low- and middle-income countries, which limits generalizability. Predictions therefore require experimental validation before being used in labelling or regulatory contexts [71,72].

Machine vision systems (MVSs), combined with machine learning, are also used for the real-time monitoring of process conditions and product quality in food plants [73]. In the longer term, such objective process data could help to characterize processing quantitatively, although this application remains to be demonstrated.

10.2. A Multidisciplinary Approach to Food Systems

Modern food system outcomes are inextricably linked to human health, environmental sustainability, and economic development. Global challenges, including food loss, resource inefficiency, continuous waste generation, and land reallocation for biofuel or animal feed, exert immense pressure on the natural resources that sustain agricultural production [74]. These complex dynamics drive unsustainable food trajectories, contributing simultaneously to environmental degradation and the global rise in non-communicable diseases [19]. At the same time, the imperative to ensure equitable access to affordable, healthy, and sustainable diets continues to escalate rapidly [75].

In response to these interconnected global challenges, the United Nations established the Sustainable Development Goals (SDGs) to foster balanced progress across the environmental, social, and economic dimensions of sustainability [76]. The SDGs provide a comprehensive framework for transforming global food systems into equitable, productive, environmentally sustainable, and nutrition-oriented networks [77]. Although food systems intersect with all SDGs to varying degrees, they directly determine the successful achievement of at least nine specific goals.

Addressing these targets requires a multidisciplinary optimization of food value chains, which encompass all input and output activities from farm to fork, including post-consumer waste management. A coordinated value chain integrates multiple organizations and stakeholders to systematically add value based on distinct product characteristics and societal requirements. Within this continuum, food processing is an important contributor to value addition, together with other factors such as plant and animal breeding and the quality of raw materials. Rather than being inherently detrimental, optimized technological processing enhances the economic viability, functional stability, and safety of food products, delivering essential benefits across the entire multidisciplinary food system framework.

11. Conclusions

The widespread adoption of the NOVA classification has undoubtedly stimulated critical discourse regarding the intersection of food processing and human health. However, the evidence synthesized in this review indicates that the UPF concept, while useful in epidemiological research, has important limitations as a solitary metric for evaluating food quality. Food processing is neither inherently detrimental nor universally beneficial. Instead, its physiological effects are strictly contingent upon the specific type and intensity of the applied technologies, the underlying food formulation, the resulting structural matrix, and their combined influence on nutrient bioavailability, digestibility, safety, and consumer behavior.

Conversely, targeted processing technologies play a vital role in preserving nutrients, improving overall digestibility, ensuring microbiological safety, extending shelf life, and significantly reducing global food waste. Furthermore, technological interventions facilitate the incorporation of functional ingredients and bioactive compounds into accessible products. Concurrently, evidence-based food reformulation remains an essential strategy for mitigating the excessive intake of sugar, salt, and saturated fats while enriching diets with beneficial nutrients. Because these technological advancements are critical for addressing interconnected global challenges related to non-communicable diseases, food security, and environmental sustainability, categorizing foods primarily by their degree of processing fails to capture the complexity of modern food systems and risks stifling essential innovation.

A scientifically robust food classification framework must integrate multiple evidence-based dimensions. These dimensions must include nutritional quality, food matrix characteristics, formulation complexity, degree of processing, metabolic health outcomes, and environmental sustainability. Existing quantitative frameworks, including the Nutrient-Rich Food Index, Nutrient Profiling Models, the Food Naturalness Index, and dietary inflammatory indices, offer compositional and complementary approaches that, despite their own limitations, can capture aspects of food quality that processing-based categories do not. Furthermore, next-generation classification systems must systematically incorporate circular economy principles and leverage digital advancements, such as predictive machine learning, to accurately characterize the holistic impact of foods on both human and planetary health.

Ultimately, the scientific community and regulatory bodies should consider complementing the processing-based concept of UPFs with compositional measures of nutritional quality and overall health impact. Replacing or complementing ambiguous processing labels with scientifically validated, quantitative criteria could provide transparent guidance for consumers, support evidence-based public health policies, incentivize responsible food innovation, and contribute to the transition toward healthier, safer, and more sustainable food systems.

Several research gaps remain. Future work should (i) develop and validate operational criteria to quantify processing separately from formulation; (ii) compare NOVA, nutrient profiling models, the NRF Index and the FNI against the same food composition databases and against health outcomes; (iii) conduct controlled feeding trials and prospective studies that disentangle processing from nutrient composition; (iv) expand food composition databases, particularly in low- and middle-income countries; (v) integrate environmental indicators, such as life-cycle assessment, into classification and labelling; and (vi) study how consumers understand and use food labels that include information on processing.

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Abbreviations

The following abbreviations are used in this manuscript:

CDS	Complex Dispersed System
DII	Dietary Inflammatory Index
DV	Daily Value
EFSA	European Food Safety Authority
FAO	Food and Agriculture Organization of the United Nations
FDA	Food and Drug Administration
FNI	Food Naturalness Index
HFSS	High in Fat, Salt, or Sugar
LIM	Nutrients to Limit
ML	Machine Learning
MPF	Minimally Processed Food
MVSs	Machine Vision Systems
NCDs	Non-Communicable Diseases
NPM	Nutrient Profiling Model
NRF	Nutrient-Rich Food Index
UPF(s)	Ultra-Processed Food/Ultra-Processed Foods
WHO	World Health Organization

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