

Aus dem Institut für Humanernährung und Lebensmittelkunde  
der Christian-Albrechts-Universität zu Kiel

# **Impact of ultra-processed food consumption on diet quality and risk of overweight**

## **Dissertation**

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**„Man braucht nichts im Lebens zu fürchten, man muss nur alles verstehen.“**

Marie Curie

## **Vorbemerkung**

Die vorliegende Dissertation wurde in kumulativer Form angefertigt und beruht auf einem veröffentlichten sowie zwei zur Veröffentlichung eingereichten Manuskripten. Zusätzlich zur fortlaufenden Seitennummerierung der Arbeit sind die Seitenzahlen des publizierten Manuskriptes abgedruckt. Das Inhaltsverzeichnis bezieht sich auf die fortlaufende Seitennummerierung der Arbeit.

*veröffentlicht mit Genehmigung der Agrar- und Ernährungswissenschaftlichen Fakultät*

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## Abbreviations

ANSES	French Agency for Food, Environment and Occupational Health & Safety
BfR	Federal Institut for Risk Assessment (Bundesinstitut für Risikobewertung)
CRP	C-reactive protein
EFSA	European Food Safety Authority
FFMI	Fat-free mass index
FFQ	Food frequency questionnaire
FMI	Fat mass index
FSA	Food Standard Agency
GLP-1	Glucagon-like peptide-1
HDL	High density lipoprotein
HTC	Holotranscobalamin
KOPS	Kiel Obesity Prevention Study
LDL	Low-density lipoprotein
MUFA	Monounsaturated fatty acids
MUP	Marker of ultraprocessing
NCD	Non-communicable diseases
NHANES	National Health and Nutrition Examination Survey
PAL	Physical activity level
PUFA	Polyunsaturated fatty acids
PYY	Peptide YY
SFA	Saturated fatty acids
SES	Socio-economic status
SSB	Sugar-sweetened beverages
UPF	Ultra-processed food

## Chapter I

### **General Introduction**

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Today's supermarket shelves are filled with far more industrially processed and packaged foods than fifty years ago, highlighting a significant shift in the food supply over the last decades (Monteiro et al., 2013). The global growth in the production, marketing, and sale of these products (Baker et al., 2020) has resulted in a corresponding increase in the consumption of highly processed foods, which are replacing both traditional unprocessed foods and freshly prepared meals. Such a dietary pattern is being increasingly investigated as a potential factor contributing to the development of overweight and obesity (Monteiro et al., 2018).

Food processing is *per se* an important achievement that has significantly benefited human development throughout evolution by making indigestible foods digestible and storable (Weaver et al., 2014). Food processing can also enhance the bioavailability of nutrients and optimize flavor in a controlled and predictable manner (van Boekel et al., 2010). The breakdown of cell walls in plant foods, for example, can facilitate the absorption of compounds such as carotenoids and polyphenols, or heat exposure to a product can facilitate the formation of desired compounds, such as those responsible for flavor and color changes (e.g., through Maillard reaction) (van Boekel et al., 2010). It has therefore played a crucial role not only in enriching the sensory experience of food consumption but also in promoting public health (Augustin et al., 2016; Knorr and Watzke, 2019; Weaver et al., 2014) and ensuring an adequate supply of food to an increasing number of people (Augustin et al., 2016; Carocho et al., 2014).

The higher demand for UPFs is in line with a modern lifestyle, characterized by a lack of time, a disruption of the conventional daily routine, and an increase in the consumption of out-of-home meals (Krüger et al., 2014). Due to their low cost, ubiquitous availability, and the need for minimal preparation (Monteiro et al., 2019), their consumption is part of everyday life. It can partially be attributed to the increase in economic prosperity, urbanization, and the rise in single-person households over the last decades (Snell, 2017; Welch and Mitchell, 2000). This development has resulted in a notable reduction in the level of knowledge required to prepare and cook food at home (Silva et al., 2023). Studies show that this decrease in home cooking, combined with the rise in consumption of prepared foods, coincides with the growing obesity epidemic (Wolfson and Bleich, 2015). This underscores the urgent need to improve home cooking skills but, more importantly, to increase awareness of what food products we eat and about their nutritional value. A variety of approaches exist for the quality assessment of food. This dissertation will focus primarily on two

approaches: the assessment of nutritional quality using the Nutri-Score and the assessment of the degree of processing of foods using the NOVA classification.

### *Assessment of the nutritional quality of foods by the Nutri-Score*

One approach to help consumers make healthier food choices at the point of purchase is through the use of the Nutri-Score label (Hercberg et al., 2022). The Nutri-Score is based on a nutrient profiling model and provides a concise overview of the nutritional quality of a food item. In several European countries, including Germany, the Nutri-Score can be voluntarily displayed as a "front-of-pack label" to assist consumers in making informed choices and to provide simplified information since the mandatory nutritional table on the back of the food packaging is often inaccessible and too technical, and therefore, rarely utilized when making purchasing decisions (Grunert et al., 2010).

The Nutri-Score offers a clear, graphical representation of a food's nutritional value (Merz et al., 2024), using a colored five-point scale from dark green (A) to dark red (E) to indicate whether the product's nutritional quality is favorable (green) or unfavorable (red) compared to other products in the same category (Hercberg et al., 2022). In order to calculate the Nutri-Score of a given product, the food is first assigned to one of the four following groups: general foods, added fats, cheese, and drinks. Afterward, assorted ingredients in 100 g per food are identified and evaluated according to their health impact (Merz et al., 2024). In line with the British nutrient intake reference values (European Food Safety Authority (EFSA), 2017), high levels of energy, saturated fats, salt, and sugar receive negative points, while fiber, protein, and the proportion of fruits, vegetables, nuts, and certain vegetable oils contribute with positive points. The total score is calculated by subtracting the sum of positive points from the negative ones, with a higher score indicating a less favorable Nutri-Score. The threshold values for the classification depend on the food group to which the product was assigned in the first step (Merz et al., 2024).

Several studies have demonstrated the potential of the Nutri-Score to impact consumer health positively (Donat-Vargas et al., 2021; Egnell et al., 2019). For instance, its widespread adoption could reduce energy intake by 9% (Egnell et al., 2019) and lower the mortality risk from cardiovascular disease and cancer (Donat-Vargas et al., 2021). However, any associated health effects were modeled rather than observed (Braesco and Drewnowski, 2023), and the scientific evidence on the

effectiveness of the Nutri-Score is still limited (Peters and Verhagen, 2024), especially because the Nutri-Score is not mandatory to be labeled on packaged foods.

### *Assessment of the degree of food processing by the NOVA classification*

To better document and measure the significant changes in the type and extent of industrial processing and formulation of food products today (Fardet, 2018; Monteiro et al., 2013), a new food categorization system called NOVA (Monteiro et al., 2019) has been introduced. This approach categorizes food based on its degree of processing, which differs from traditional food classification systems that categorize foods based on their botanical and animal origin or the nutrients or ingredients they contain (Fardet and Boirie, 2014). This shift in perspective has prompted a discussion about the concept and terminology associated with the degree of processing (Sadler et al., 2021).

The NOVA system was developed in 2009 by Carlos Monteiro and is based on the assertion that the rising consumption of highly processed foods contributes to the increasing prevalence of non-communicable diseases (NCDs, Monteiro, 2009). Monteiro posits that these associations can only be explained by considering the food as a whole (Monteiro et al., 2019). The prevailing reductionist view of individual food components has led to a narrow understanding of food as merely the sum of its nutrients. A holistic approach views foods as intricate combinations of nutrients that can interact with one another depending on their composition. This is why the nutritional value of foods cannot be determined solely based on their ingredients (Monteiro et al., 2019). The NOVA classification is therefore built on the assumption that all physical, biological, and chemical processing techniques employed by the food industry also exert an influence on the health evaluation of foods, as the structure and composition of the entire food are altered. The NOVA classification system categorizes foods into four distinct groups (Monteiro et al., 2019):

The first NOVA category includes unprocessed and minimally processed foods. Unprocessed foods are in their natural state and encompass the edible portions of plants and animal products, like fruits, vegetables, legumes, or eggs. Minimally processed foods are unprocessed foods altered by industrial processes like removal of unwanted parts, drying, crushing, pasteurization, or freezing before consumption. The objective of minimal processing is to preserve the food matrix but to extend the shelf life of the food, thereby enabling stable storage and making the preparation easier.

Consequently, the NOVA 1 category encompasses foods such as milk, yogurt, and meat, as well as flour and pasta. In some cases, minimally processed foods contain additives that enhance shelf life.

The second NOVA category (NOVA 2) pertains to substances obtained directly from NOVA 1 foods known as culinary ingredients, including oils, fats, salt, and sugar. It is important to note that these food components are typically combined with other foods, as they are rarely or never consumed independently.

The third NOVA category (NOVA 3) includes processed foods, such as canned vegetables and fruits, as well as freshly baked bread and cheese. The primary objective behind processing these simple industrially manufactured food products is to prolong their shelf life and enhance their sensory attributes. As a result of this processing, most foods in this category consist of multiple ingredients or components, and they are easily recognizable as modified versions of unprocessed foods. NOVA 3 foods can contain additives that prolong shelf life but no additives to make the product more palatable.

Ultra-processed foods (UPF, NOVA 4 category) are defined as foods that have undergone a series of industrial processing steps and consist of multiple ingredients (formulation). These foods typically contain a multitude of ingredients derived from inexpensive raw materials, like corn, wheat, rice, sugar, and palm oil. Furthermore, various additives are employed (e.g., preservatives, colorants, flavorings, sweeteners, and emulsifiers) not only to extend the food's shelf life and facilitate preparation but also to enhance palatability. UPFs encompass a range of products, including those that are ready-to-eat or ready-to-heat, as well as confectionery, soft drinks, and ready-made sauces (Monteiro et al., 2019).

### *Consumption of ultra-processed foods*

The implementation of the NOVA classification system was followed by numerous studies examining the contribution of UPFs to daily energy intake. Comparable dietary patterns are observed in several high-income countries with an alarming prevalence of UPF consumption. For instance, representative studies published since 2016 have shown that UPFs contributed up to 48% of daily caloric intake in Canada (Moubarac et al., 2017), 54% in the UK (Rauber et al., 2020), and 56% in the USA (Steele et al., 2019). In Germany, data from the National Nutritional Survey II from 2007 show that UPFs constituted 38% of the daily energy intake (Mertens et al., 2022). Comparatively, lower

consumption of UPFs is observed in southern European countries, like Spain and Italy with 24% and 10% of energy intake from UPF, respectively (Blanco-Rojo et al., 2019; Bonaccio et al., 2021). This observation can be attributed, at least partly, to the maintenance of tradition and food culture, as evidenced by the prevalence of the classic Mediterranean diet, in which unprocessed foods are prepared at home and primarily consumed in family meals (Pieniak et al., 2009). However, it is becoming apparent that the younger generation, in particular, is increasingly deviating from traditional dietary patterns, which is expected to result in a continued increase in UPF consumption, even in regions with more traditional dietary habits (Calixto Andrade et al., 2021; Pieniak et al., 2009). In middle- and low-income countries, UPFs have so far represented a relatively modest proportion of daily energy intake (Baker et al., 2020). Nevertheless, the data indicate that UPF sales continue to expand in all regions and in the majority of countries, with the most rapid growth occurring in upper and lower middle-income countries (Baker et al., 2020).

On an individual level, high consumption of UPF is associated with sociodemographic characteristics such as urban living and being unmarried, single, separated, or divorced, (Dicken et al., 2023) whereas education, income, and socioeconomic status (SES) showed varying associations, depending on the country. In contrast, age exhibited a consistent inverse correlation with UPF intake (Dicken et al., 2023). Recent data indicate that children and adolescents are the leading consumers of UPFs (Neri et al., 2022). Furthermore, dietary habits appear to be a significant factor. A cross-sectional study of 21,212 adults from the French NutriNet-Santé cohort revealed that a higher avoidance of animal-based products was associated with higher consumption of UPFs (Gehring et al., 2021).

Numerous epidemiologic studies have shown an association between the consumption of UPFs and an increased risk of overweight and obesity (for review, see Chen et al., 2020). Cross-sectional studies conducted in Brazil, the USA, and the UK with 8,977, 15,977, and 6,143 adults, respectively, demonstrated that individuals with the highest consumption of UPFs exhibited a higher BMI and a higher waist circumference compared to those with low consumption (comparison of the highest vs. lowest quartiles/quintiles) (Juul et al., 2018; Rauber et al., 2020; Silva et al., 2018). The highest consumption of UPFs was associated with a 31% - 48% higher odds ratio for overweight and a 41% - 90% higher odds ratio for obesity compared to the lowest consumption (Juul et al., 2018; Rauber et al., 2020; Silva et al., 2018). A 10% increase in UPF intake was linked to an 18% and 17% higher prevalence of obesity in men and women, respectively (Rauber et al., 2020). Prospective

cohort studies from Spain, Brazil, and France (8,451, 11,827, and 110,260 adults) reinforced these findings, demonstrating that the highest consumption of UPFs (comparison between the highest and lowest quartiles) was associated with an increased likelihood of developing obesity by 20% - 26% over periods of 4 to 9 years (Beslay et al., 2020; Canhada et al., 2020; Mendonça et al., 2016). All these studies show an impressive increase in the prevalence of overweight in parallel with an increase in the consumption of UPFs. However, there is a lack of current data from Germany and, more crucially, a need for greater insights into the underlying mechanisms using a more detailed assessment of the qualitative aspects of UPFs.

### *Objectives*

This dissertation investigates the conceptual differences between the classification of foods based on the nutritional value (Nutri-Score) and on the degree of processing (NOVA), as well as ultra-processed food consumption in children, adolescents, and young adults in Germany and its impact on diet quality, nutritional status and overweight.

The following objectives are addressed:

- I. Assessing the implementation of the Nutri-Score in Germany after its use was legally permitted on packaged foods and comparing the classification of foods using the Nutri-Score and the NOVA system.
- II. Examining ultra-processed food consumption, its impact on overweight, and its association with weight trends from childhood and adolescence to young adulthood in the Kiel Obesity Prevention Study (KOPS).
- III. Analyzing the nutritional status and diet quality in first-year students with different plant-forward eating patterns and the nutritional quality of ultra-processed foods compared to processed foods.

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## Chapter II

### **Implementation of the Nutri-Score**

#### **First results and a comparison with the NOVA classification**

Svenja Fedde, Sophie Büttner-Koch, Vera Plähn, Anja Bosy-Westphal

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# Implementation of the Nutri-Score

## First results and a comparison with the NOVA classification

Svenja Fedde, Sophie Büttner-Koch, Vera Plähn, Anja Bosy-Westphal

### Abstract

Front-of-pack labels like the Nutri-Score can help consumers to compare foods within a product group in order to make a more nutritious choice. However, other dimensions of foods, such as the degree of processing, are not considered.

The aim of the study was to evaluate the labeling frequency of the Nutri-Score shortly after the legally compliant, implementation in the German food retailing sector, and to compare the nutritional composition of the food using the Nutri-Score with the degree of processing according to the NOVA classification. Of 2,333 packaged products examined 12% were labeled with a Nutri-Score at the time of data collection and showed predominantly category A and B (highest nutritional quality categories).

Classification of the food products according to NOVA showed that 100% of the products labeled with Nutri-Score C, D, or E and 41% of the products labeled A were also classified as ultra-processed.

In order to improve food labeling with regard to the prevention of diet-related diseases, it would be useful to extend the front-of-pack-label by taking the degree of food processing into account.

**Keywords:** front-of-pack label, nutrition labeling, Nutri-Score, NOVA classification, ultra-processed food, degree of processing.

### Introduction

In order to prevent obesity and diet-related diseases, the German Federal Ministry of Food and Agriculture (BMEL) introduced the National Reduction Strategy for Sugar, Fats and Salt in finished products in 2018 [1]. In addition, using easy-to-understand food labeling, the nutritional competence of consumers can be further strengthened. Specifically, it is intended to counter the fact that consumers often rate the mandatory nutritional facts table on the back of the package too difficult to read and understand and therefore rarely use it as a basis for purchasing decisions [2]. For this reason, the voluntary use of the so-called Nutri-Score has been legally permitted on packaged foods in Germany since November 2020 [3].

The Nutri-Score is a front-of-pack label (FoPL) that simply summarizes and graphically displays the nutritional quality of food [4]. For this purpose, a five-point scale from dark green (A) to dark red (E) is used to indicate whether the nutritional quality of a product is rather favorable or unfavorable compared to other products within the same category (• Figure 1) [3]. To calculate the Nutri-Score of a product, its ingredients per 100 g of food are determined and ranked according to their health impact by assigning positive or negative points [5]. Based on the British reference values for nutrient intake [6], high levels of energy, saturated fat, salt, and sugar are scored negatively, while fiber, protein, the proportion of fruits, vegetables, and nuts, and certain vegetable oils are included as positive factors in the score. For the total score, the sum of the positive points is subtracted from the sum of the negative points. The higher the total score, the "poorer" the Nutri-Score. The total Nutri-Score can also be positively influenced by compensating negative points that a product receives, for example, due to a high sugar content, with positive points due to healthy ingredients (e.g. dietary fiber) [5]. However, not every reformulation leads to a change in the Nutri-Score. Only a maximum of 3 points is needed to raise the Nutri-Score

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from B to A, whereas up to 8 points are needed to improve it from D to C [3].

First results of the National Reduction Strategy show that manufacturers have reduced sugars, fats, and salt in their products [7]; however, these changes have so far been too small. The potential of the Nutri-Score to positively influence consumer health has already been demonstrated in several studies [8, 9]. For example, the widespread introduction of the Nutri-Score could lead to a reduction in energy intake in the population by an average of 9% [8] and a reduction in mortality from cardiovascular disease and cancer [9].

While an evaluation of food quality based on its nutrients is common, the degree of processing is rarely considered. Numerous epidemiological studies already show that a regular high consumption of so-called ultra-processed foods increases the risk for overweight and obesity as well as for type 2 diabetes mellitus type 2, cardiovascular diseases or cancer [10]. Classification systems such as NOVA, which has already been used in many studies [11], form the basis for classifying foods according to their degree of processing [12]. According to NOVA, ultra-processed foods are characterized by an formulation, that results from several industrial processes. In most cases, they contain ingredients that are produced by those high-technology processes (e.g., hydrolyzed proteins, maltodextrin, invert sugar) and therefore serve as markers of "ultra-processing" [13]. Also, a variety of additives are used (e.g. colorants, flavors, sweeteners, and emulsifiers) to make these foods ready to eat, hyperpalatable and prolong shelf life [12]. Although ultra-processed foods are often energy-dense and high in salt, sugar, and fat, these are no criteria for NOVA classification. Thus, there are clear differences between the concepts of the Nutri-Score, which evaluates nutritional quality, and the NOVA classification, which is based on food processing [14], both pursue the same goal: to evaluate food composition in terms of its health effects.

Therefore, the aim of this study was, on the one hand, to identify how many products have already been labeled with the Nutri-Score in the first few months after its introduction in Germany, and secondly, to compare the classification of foods using the Nutri-Score and the NOVA classification.

Category	Designation	Food examples
1	savory frozen products	Frozen fish, meat-, poultry-, vegetable-, potato-products, pizzas, ready-to-heat-products
2	sweet frozen products	Frozen ice cream, fruit, desserts, cakes, sweet pastries, rolls, croissants, doughs
3	yogurts/milk desserts	Yogurts, puddings, milk snacks, vegan alternatives
4	cereals	Mueslis, cornflakes, oat flakes, extrudates, fruit and muesli bars

Tab. 1: Overview of the selected product categories

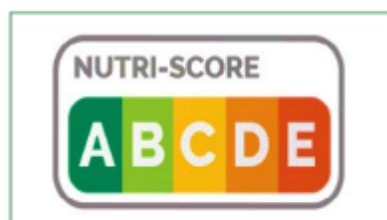


Fig. 1: Nutri-Score Label

## Methodology

In this study, food surveys were conducted (not strictly simultaneously and in random order) from December 2020 to March 2021 in four markets of the German food retail sector, including the discounters Aldi Nord (Aldi Group), Penny (REWE Group) and Lidl (Schwarz Group) as well as the online store of the REWE supermarket (REWE Group). Proportionately more discounters were included since these are the most important group of suppliers in the German food retail sector [15].

The sample was therefore heterogeneous, but not representative. Food products from four different categories were investigated: savory frozen products, sweet frozen products, yogurts /milk desserts, and cereals (• Table 1). These categories were selected because they include a particularly large number of packaged and processed products for which, in accordance with EU-Regulation 1169/2011, there is an obligation to declare certain nutritional values and therefore the Nutri-Score can be applied.

For each category, all available foods were identified and products with a Nutri-Score label were documented, including Nutri-Score labels at the point-of-sale. It was also documented whether the food was from a retailer-brand or a manufacturer-brand.

The food products labeled with a Nutri-Score were assigned to one of the four groups of the NOVA classification according to the purpose and extent of processing [12]:

- Group 1 - unprocessed and minimally processed foods
- Group 2 - processed ingredients
- Group 3 - processed foods
- Group 4 - ultra-processed foods

Open Food Facts, which is an open-source database, was used to obtain the NOVA classification [16].

The data analysis was carried out with the program Microsoft Excel 2017 and the statistics and analysis software IBM SPSS Statistics 26.



## Results of the survey in the food retail trade

Out of a total of 2,333 food products surveyed, 278 products (11.9%) were labeled with the Nutri-Score. In comparison to the other retailers, Penny (REWE Group) had the most Nutri-Score labeled foods (32.6%). Differences in the distribution of the Nutri-Score could also be found between product categories. The highest proportion of labeled products was found in the category "savory frozen products" with 20.5%, followed by "yogurts/milk desserts" with 12.5%. In the category "sweet frozen products" 8.9% and in the "cereals" category, only 3.4% of the products were labeled with the Nutri-Score. In all product categories and across all food retailers, Nutri-Score categories A and B (highest nutritional quality categories) were the most common at 62%. Nutri-Score category C, was labeled on 26% of the products and category D on 9%. Nutri-Score E, indicating the worst nutritional quality was found on 3% of the food products (• Figure 2).

• Figure 3 shows that the distribution of the Nutri-Score differs according to the product category. The category "sweet frozen products" contained by far the largest share of both Nutri-Score levels D and E with 73%, while the category "yogurts/dairy desserts" included the largest share of foods labeled A or B with 81%.

The classification according to NOVA showed that 79% of all products labeled with the Nutri-Score are ultra-processed foods. Foods with a Nutri-Score rating of levels C, D, and E are 100% ultra-processed according to the NOVA classification (NOVA-Group 4) while also foods labeled with a Nutri-Score B predominantly belong to NOVA-Group 4. The largest proportion of unprocessed and minimally processed foods is found among the products that were labeled with the Nutri-Score A. Nevertheless, 41% of these products can also be classified as ultra-processed (• Figure 4).

## Discussion

In the food retail sector examined, the Nutri-Score was still rarely used in the first three months after its introduction, with only 12% labeled products within the examined categories. However, even in Belgium, only 10% of the total food supply was labeled with the Nutri-Score in the first year after its introduction [17] and approximately 90% of those labeled foods were private label products from two large food retailers (retailer-branded products), while the remaining products were manufacturer-branded products (national brands) [17].

In contrast, in this study in the German food retail sector, shortly after the legally compliant introduction of the Nutri-Score, it was observed that only 33% of the foods labeled were private label products and therefore national brands dominated. Similar results were seen in the studies by Marczuk et al., who also looked at the distributors of the Nutri-Score in Germany based on the Global New Product Database [18].

The percentage of manufacturer-branded products (national brands) labeled with the Nutri-Score was 78.6% of all labeled products in the reference period of this study from May 2019

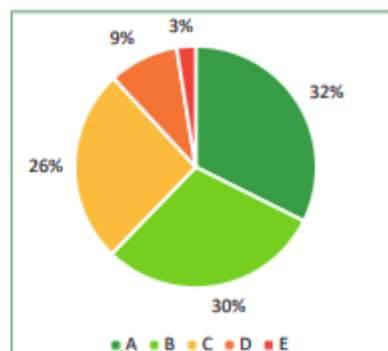


Fig. 2: Occurrence of the individual Nutri-Score levels summarized in the four product categories.

to November 2020. However, the authors assume that the share of private-label products will increase over time, similar to the situation in France. Some food retailers, already had the Nutri-Score-labeling on their private-labels as part of their market strategy [19].

## Distribution of the five Nutri-Score Categories

Only a minor share of the foods analyzed were labeled with a Nutri-Score E or D, while the majority of foods labeled with a Nutri-Score (89%) exhibited level A, B, or C. Marczuk et al. also showed for the period before the introduction on the German market (May 2019 to November 2020) that favorable Nutri-Score labels predominated (A, B, and C labels in 91.5% of products) and the proportion of products with a Nutri-Score D and E was only 8.5% [18]. Similar labeling behavior was also found in Belgium, where 74% of products were labeled with A, B, or C one year after introduction [17], and in France, where favorable A/B labeling also predominated on foods within the first two and a half years, with more than 82% of labeled products [18]. A similar labeling behavior was also found in Belgium, where 74% of products were labeled with A, B, or C, one year after introduction [17], as well as in France, where favorable A/B labeling also predominated on foods within the first two and a half years, with more than 82% of labeled products [18].

These results suggest that products that received a more favorable Nutri-Score were preferentially labeled. However, continuous data from France also shows that the proportion of more unfavorable labeling (Nutri-Score D and E categories) increases over time [18].

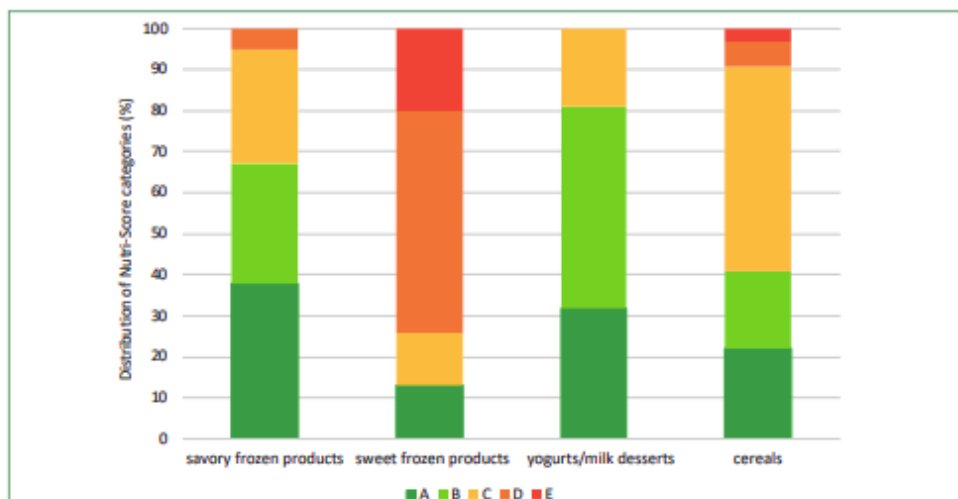


Fig. 3: Distribution of the five Nutri-Score levels within the respective defined product category.

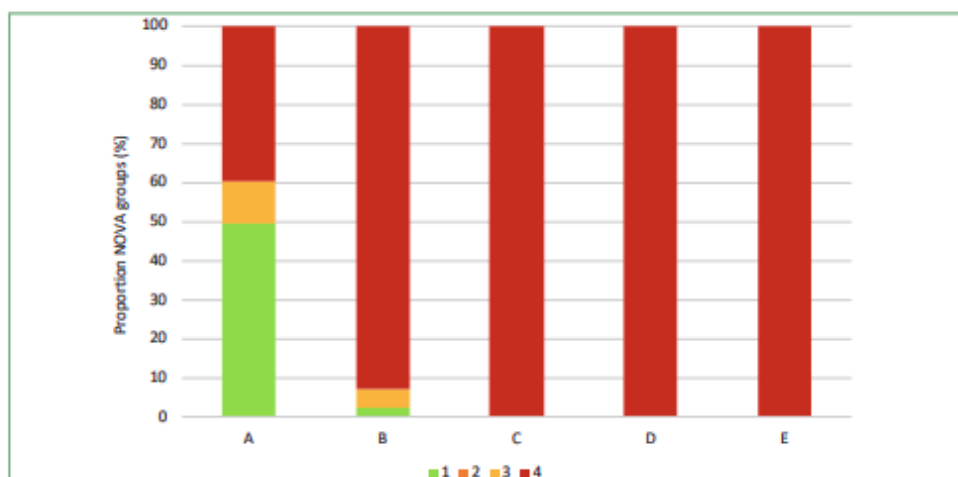


Fig. 4: Proportions of the four NOVA levels within each Nutri-Score. (Nutri-Score A significantly different from the other Nutri-Scores B-E, Kruskal-Wallis:  $p < 0.001$ ; Dunn-Bonferroni:  $p < 0.01$ ).

This can probably be attributed to the mandatory labeling of all products of a brand within two years of the company's registration. The food products in the "yogurts/milk desserts" category had the best Nutri-Score ratings compared to the other product categories. Especially natural yogurts, vegan yogurt alternatives and plain yogurts with added fruit, with a low fat and salt content were labeled with a Nutri-Score. The largest proportion of the two categories D and E indicating the lowest nutritional quality (73%) was found in the product category "sweet frozen products". This is due to the high proportion of high-sugar and high-fat products such as ice cream, cakes, tarts and small baked goods. Consumers must know how to interpret the Nutri-Score correctly and therefore be aware that it is intended to be used for compar-

son within a product category. A frozen pizza with a Nutri-Score A does not mean that this product should be on the menu every day, but that this product has a better nutritional composition than other pizzas. Also the allocation of a food to the corresponding product group is not easy to understand for consumers. For example, a chocolate flavored drink-powder is calculated according to the points table for foodstuffs and not according to the points table for beverages, since the ready-prepared product is rated as a dairy product. As a food product, the product thus gets a B printed on



the packaging, but as a beverage it would be labeled with E (♦ Figure 5) [20].

#### Comparison of NOVA and Nutri-Score

Dréano-Trécant et al. already investigated the ability of the Nutri-Score regarding to discriminate the nutritional quality of foods and its consistency with national dietary recommendations in eight European countries [21]. They have shown that the large majority of recommended foods, such as fruits, vegetables, legumes, and nuts, as intended, have a better Nutri-Score compared to sweet, fatty and salty products.

In line with the results of our study, Dréano-Trécant et al. have also shown that packaged but unprocessed foods such as frozen fruits and vegetables, meat and fish, and natural yogurt accounted for the majority of Nutri-Score A ratings in the respective product categories and that processed products were mainly classified with Nutri-Score C, D or E [21].

In the present study in the German food retail sector, the foods in the Nutri-Score C, D, and E categories were 100% assigned to NOVA 4. But also over 90% of the products with Nutri-Score B and even 41% of the products with Nutri-Score A fell into the group of ultra-processed foods according to the NOVA classification (♦ Figure 4). These are, for example breakfast cereals, vegan yogurt alternatives or frozen potato products (e.g., wedges).

The Nutri-Score is not designed to consider the degree of processing and packaged foods labeled with a Nutri-Score may therefore occupy different classifications in the NOVA system. However, the results of the present study show that a comparably high proportion even of the favorable Nutri-Score labels are found on ultra-processed foods.

Examples of products with the same favorable Nutri-Score within a category but very different levels of processing are fruit yogurts: There are low processed fruit yogurts with a favorable Nutri-Score rating that consist of few ingredients such as yogurt and fruit and provide additional nutrients due to the fruit content.

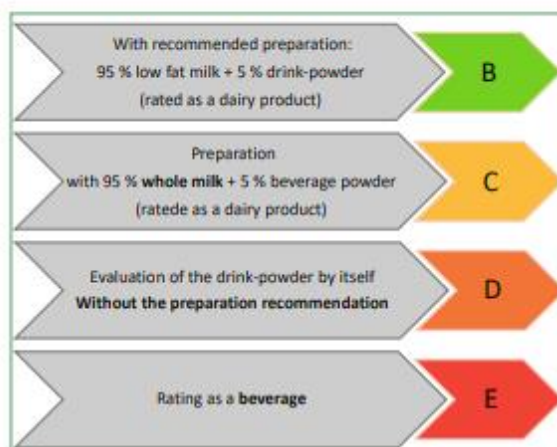


Abb. 5: Nutri-Score for a chocolate drink-powder depending on the preparation method [mod. nach (20)]

On the other hand, there are also those with a likewise favorable Nutri-Score that contain cosmetic additives such as colorings and flavorings in order to save on expensive ingredients such as fruit.

Since both products within a product category have the same Nutri-Score, consumers consider them to be of equal nutritional value. However, this shows that possible negative effects due to increased consumption of ultra-processed foods are in some cases not considered in the concept of the Nutri-Score. For example, the current failure to consider additives and highly processed ingredients in the calculation of the Nutri-Score means that e.g. an apple spritzer made of natural ingredients receives a Nutri-Score of C, while a sugar-free lemonade with coloring, flavoring, and sweeteners can be labeled with a better Nutri-Score B.

Equally, examples to show the opposite can be found where foods have an unfavorable Nutri-Score without necessarily being ultra-processed. For example, there are products such as ketchup or tomato sauce that do not use indicators of ultra-processing such as modified starch, thickeners and sweeteners and are therefore not classified as ultra-processed foods, but due to a high salt and sugar content they fall into the Nutri-Score category for the lowest nutritional quality.

Linking the conceptual differences of the Nutri-Score and NOVA classification should be considered in response to the above-mentioned "gaps" in the assessment, as well as the increasing evidence for health risks associated with consumption of ultra-processed foods. Thereby, the presumed mechanisms for ultra-processed foods are partly consistent with the Nutri-Score dimension (nutritional quality) and, in addition to poor carbohydrate and fat quality and low nutrient density [22], relate primarily to an altered food matrix, which shows an influence on satiety and glycemic index [23], as well as the presence of process- and packaging-dependent contaminants (e.g., trans fatty acids, phthalates, bisphenols) [24, 25]. Additives frequently present in ultra-processed foods have been associated with adverse health effects, although to date these have so far been studied almost exclusively in animal studies and are discussed controversial [26-28].

One way to integrate the degree of processing of food into the algorithm for calculating the Nutri-Score is the Siga classification [13]. This is an extended form of the NOVA system with additional subgroups, in which so-called mark-



ers for ultra-processing such as additives, highly processed ingredients such as maltodextrin, and ultra-processing of the end product are taken into account [13, 29].

## Limitations

The data collection in the three food retail markets and the online store was not performed strictly simultaneously over a period of 3 months, which could have led to a bias in the results, especially in the dynamic initial phase of the introduction of the Nutri-Score. In addition, EDEKA (Edeka Group), the food retailer with the highest sales in Germany, was not considered, which may also have influenced the results. After the end of the data collection, some food retailers announced the introduction of the Nutri-Score on their retail-branded items and explicitly advertise this. Therefore, it can be assumed that in the meantime more products overall and proportionately more retail-branded products are labeled with the Nutri-Score.

In addition, the food classification according to the degree of processing in this study may be incorrect because the OpenFoodFacts database was used to determine the NOVA classification.

This database processes nutritional information and ingredients of foods and beverages provided by users. Incorrect entries may have caused incorrect NOVA levels to be displayed.

the NOVA system based on food processing. The NOVA classification considers the use of additives such as emulsifiers, stabilizers, preservatives or colorants and flavorings and other markers of ultra-processing. If manufacturers change their recipes to advertise a better Nutri-Score, there could be an increased use of additives to maintain taste, consistency and a long shelf life that is not reflected by a change in the Nutri-Score. To combat this, the degree of processing should be integrated into the Nutri-Score.

## Conclusion and outlook

The implementation of the Nutri-Score is an important step towards helping consumers choose healthier alternatives. A complete and thus mandatory labeling of all packaged foods, as proposed by the EU Commission in the context of the "Farm to Fork" strategy [30], would be desirable.

Food retail surveys should be repeated periodically to evaluate how the implementation of the Nutri-Score is progressing and to investigate whether the prevalence of the labeling with the unfavorable Nutri-Score D and E levels is increasing as suspected and as shown in France. At the same time, prospective studies should investigate the actual health effects associated with the application of the Nutri Score.

However, it should be considered to include other health-related criteria in the calculation of the Nutri-Score. For example, a diet, containing more plant-based foods and less meat is associated with both, better dietary quality and with a lower environmental impact [31]. The so-called Eco-Score is intended to indicate exactly this environmental impact of food and is already labeled on some food packaging in France. A European citizens' initiative is even calling for a mandatory labeling throughout Europe [32], which could also be communicated as an additional aspect in the Nutri-Score. This would have the advantage that consumers would not be overwhelmed by another, new label.

In terms of optimizing nutritional quality, more attention should be drawn to the degree of food processing. Therefore, the classification of foods according to the Nutri-Score was compared with

**Conflict of interest**

The authors declare that there is no conflict of interest.

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## Chapter III

# **Ultra-processed food consumption and overweight in children, adolescents and young adults: Long-term data from the Kiel Obesity Prevention Study (KOPS)**

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## **Ultra-processed food consumption and overweight in children, adolescents and young adults: Long-term data from the Kiel Obesity Prevention Study (KOPS)**

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**Abstract**

*Objective:* The aim was to assess ultra-processed food (UPF) consumption, its impact on overweight, and its association with weight trends from childhood and adolescence to young adulthood.

*Methods:* Long-term UPF consumption by NOVA (13.3 y) was analyzed (children/adolescents and adults, n = 182) in the Kiel Obesity Prevention Study (KOPS, n = 10,750).

*Results:* In children/adolescents (13.1 ±1.9 y), a UPF-based dietary pattern showed an inverse association with BMI-SDS and fat mass index (males: r= -0.301, p = 0.01; r= -0.376, p = 0.001; females: r= -0.315, p < 0.001; r= -0.282, p = 0.003). Longitudinal analysis indicated that UPF consumption in childhood and adolescence was correlated with the UPF consumption in adulthood among females (r= 0.272; p = 0.004) but not males. In young adults (26.7 ±2.2 y), UPF consumption accounted for nearly 50% of daily energy intake and was higher with overweight compared to normal weight and in incident overweight compared to persistent normal weight (both p < 0.05). High UPF consumption was associated with markers of poor diet quality (lower intake of fiber, higher intake of salt, and energy-dense food, all p < 0.05).

*Conclusions:* High UPF consumption in young adults was associated with both prevalence and incidence of overweight from childhood and adolescence to adulthood.

## Introduction

Dietary patterns established during childhood and adolescence can persist into adulthood<sup>1</sup> and influence the risk of overweight and obesity.<sup>2</sup> Since childhood overweight often sustains over time, observing weight trends can provide not only valuable insights into how the prevalence and persistence of overweight and obesity are evolving but also when significant periods of weight gain tend to occur more frequently.<sup>2</sup> Especially the transition period from adolescence to adulthood has received less attention, with only a few studies examining the different trajectories of BMI during this life stage.<sup>3,4</sup> Understanding those specific time points is crucial for gaining insight into time-dependent determinants of overweight and obesity and preventing excessive weight gain.<sup>3</sup>

Adolescents and young adults tend to exhibit less healthy dietary behaviors compared to older individuals, characterized by high consumption of energy-dense, nutrient-poor ultra-processed foods (UPF).<sup>5</sup> According to the NOVA classification system, UPF are characterized by containing a variety of highly processed ingredients and additives (e.g., colorings, flavors, sweeteners, and emulsifiers) and are often high in energy, salt, sugar, and saturated fat, combined with a low nutrient density.<sup>7</sup> They are hyper-palatable, cheap, ready-to-eat, and are usually heavily advertised,<sup>8</sup> especially to children.<sup>9</sup> Accordingly, UPF already contributes to more than half of the daily caloric intake in countries like the US,<sup>10</sup> Canada,<sup>11</sup> and the United Kingdom.<sup>12</sup> Current data for Germany are lacking but are crucial because of the fast-paced development of novel food products.<sup>8</sup>

Recent data have shown that children and adolescents are already the leading consumers of UPF in some high-income countries,<sup>13</sup> and most cohort and cross-sectional studies have found that an increase in UPF consumption was associated with a higher prevalence of overweight and obesity among children and adolescents (for review, see<sup>14</sup>). Also in adults, several epidemiological studies have shown an association between high UPF consumption and overweight and obesity (for review, see<sup>15</sup>). To our knowledge, only one longitudinal study has examined UPF consumption in childhood and its association with adiposity trajectories in adulthood.<sup>16</sup> Further research is required to understand the potential long-term impact of UPF consumption on dietary habits, the risk of overweight and the mechanisms that might explain any increase in risk.

Therefore, the present study had four aims: (i) First, to compare adherence to an UPF-based dietary pattern in childhood and adolescence with UPF consumption in young adulthood; (ii) second, to analyze the association between weight trends and UPF consumption; (iii) third, to investigate the

impact of the current German UPF consumption on health outcomes in young adults; (iv) forth, to identify diet quality aspects that may explain the adverse health outcomes by UPF consumption.

## Methods

### *Study population*

Data were collected as part of the Kiel Obesity Prevention Study (KOPS), which commenced in 1996 and recruited 10,750 children and adolescents in in the 4<sup>th</sup> and 8<sup>th</sup> grades. The main cohort was representative of all 5- to 7-year-old children in Kiel, Germany.<sup>17,18</sup> The aims, study design, and recruitment procedure are described elsewhere.<sup>18,19</sup> From 2018 to 2020, a total number of 313 participants aged 23 to 30 years who had previously participated in KOPS were examined again in order to monitor weight trends from childhood and adolescence up to the age of young adults.

The 313 participants were the responders to an invitation to follow-up that was sent by post via the last address provided by their parents. The study was registered at the German Clinical Trials Register as DRKS00014648. Participation at all time points was voluntary and without any eligibility criteria except the willingness to participate.

### *Anthropometric measurements*

According to standard procedures, height and weight measurements were performed by trained observers from the Institute of Human Nutrition and Food Science, Kiel University. Body weight was measured to the nearest 0.1 kg using a calibrated digital scale (seca GmbH, Hamburg, Germany) with subjects in underwear. Body height was assessed to the nearest 0.1 cm using a stadiometer (seca GmbH, Hamburg, Germany). BMI was calculated as kg/m<sup>2</sup> from weight and height. For children and adolescents, BMI was converted into an SD score (BMI-SDS) using German BMI percentiles by Kromeyer-Hauschild et al. to determine overweight status.<sup>20</sup> Overweight was defined as the 90. percentile for children and adolescents and as BMI 25-30 kg/m<sup>2</sup> for adults, while a BMI >30 kg/m<sup>2</sup> indicated obesity in adults.

In children and adolescents, body composition was assessed by bioelectrical impedance analysis (BIA) using a tetrapolar BIA device with hand-to-foot electrodes (BIA 2000-C; Data Input GmbH, Darmstadt, Germany). Fat free mass (FFM) was calculated using a BIA algorithm specifically developed and cross-validated for children and adolescents in our lab using air displacement plethysmography as a reference.<sup>21</sup> Fat mass (FM) was calculated from the difference between body weight and FFM. In

adults, body composition was assessed using air displacement plethysmography (BodPod Cosmed, Werneck, Germany). FM and FFM at both measuring times were normalized by height squared to fat mass index (FMI: kg FM/ m<sup>2</sup>) and fat-free mass index (FFMI: kg FFM/ m<sup>2</sup>).

#### *Blood samples*

In adults, blood samples were taken after an overnight fast to measure blood lipids (total cholesterol, HDL, and LDL, triglycerides), glucose, insulin, and C-reactive protein (CRP) levels. The analysis of all blood parameters was performed in an accredited and certified laboratory (Labor Dr. Krause & Kollegen MVZ GmbH, Kiel, Germany). Blood lipids were assessed by enzymatic color measurements. Plasma glucose was measured by hexokinase method and serum insulin concentrations were measured by chemiluminescence microparticle immunoassay. CRP was assessed using an immunoturbidimetric test. Participants with elevated CRP levels (>3 mg/dl) were excluded from the statistical analysis (n 31). Given that the study population comprised young and healthy adults, it was assumed that a CRP value above 3 indicates the presence of an acute infection.

#### *Pubertal Stage*

Pubertal development (female breasts, male genitalia development, and pubic hair growth in both sexes) was self-estimated by children and adolescents using standardized pictures of Tanner staging on a scale of 2–5. The pubertal stage of 4<sup>th</sup> graders was assumed to be pre-pubertal (scale 1).

#### *Sociodemographic and lifestyle data*

In children and adolescents, sociodemographic data were collected using self-reported questionnaires filled in by parents. Socioeconomic status (SES) in children and adolescents was determined by parental education level based on the highest level attained by either parent and divided into three categories: (1) low  $\leq 9$  school years, (2) middle  $\geq 10$  to  $< 12$  school years, (3) high  $\geq 12$  school years. Single-parent families were classified according to the school education of the single parent. The parental questionnaire also assessed sports activity of the children and adolescents based on training hours in a sports club. The activity was divided into 1. zero hours (no sport in a club), 2. up to one hour per week, 3. one to two hours per week, and 4. more than two hours per week. In adults, income, smoking status, physical activity and SES (based on their highest educational level) were assessed using a lifestyle questionnaire.

### *Dietary assessment*

In children and adolescents, dietary intake was assessed by validated food frequency questionnaires (FFQ),<sup>22</sup> and the food items were categorized: (1) never; (2) 1–2 times/week; (3) 3–5 times/week; and (4) daily. In adults, food consumption was evaluated using 24h-recalls. For the analysis, two 24h-recalls had to be completed. The first was conducted on-site by trained observers, whereas the second was collected by phone 7 to 14 days later. Averaged energy and macronutrient intake from the two assessed days were calculated using Prodi® 6.11 (Wissenschaftliche Verlagsgesellschaft, Stuttgart, Germany) based on the German Nutrient Database (BLS, Bundeslebensmittelschlüssel) Version 3.02. For brand products, we manually added all nutritional compositions provided by the manufacturer. The Black method,<sup>23</sup> which is based on the Goldberg cut-off,<sup>24</sup> was employed to exclude those who had underreported their dietary intake (n = 32). This was done on the basis of the ratio of the reported daily energy intake and the estimated basal metabolic rate, which was calculated using the Schofield equation.

### *Classification of food processing by NOVA*

All reported food items were categorized according to the extent and purpose of food processing following the NOVA classification system.<sup>7</sup> This system differentiates between four food groups: 1. unprocessed and low-processed foods, 2. processed ingredients, 3. processed foods, and 4. ultra-processed foods (UPF). In children and adolescents, 12 out of 21 food items from the FFQ were classified as UPF. A UPF score was calculated by adding partial scores based on the consumption frequency of each UPF (0, no consumption; 1, consumed once a week; 4, consumed several times a week; 7, consumed every day). The score for consumption of UPF varied between 0 and 84 points, with a higher score indicating a greater intake of these products.

In adults, every food item assessed by the two repeated 24h-recalls was categorized according to NOVA in consensus by a team of two researchers and one dietitian, with the most conservative classification option chosen in case of uncertainty. Home-made foods were identified and decomposed using standardized recipes, and the NOVA classification was applied to their ingredients.

### *Statistical analysis*

Data were analyzed using IBM® SPSS® Statistics for Windows (version 28.0 Somers, NY, USA). Descriptive statistics of the study population are reported as means and standard deviations unless otherwise specified. Normal distribution was checked via the Kolmogorov–Smirnov test. The non-

parametric Mann-Whitney U-test and Chi<sup>2</sup>-test were used to evaluate sex differences in subject characteristics, as well as differences regarding BMI and SES between the total population and the analyzed subsample. In children and adolescence, Spearman's correlation and non-parametric Kruskal-Wallis test were used to determine the association between UPF score and body composition as well as the differences in UPF score between SES groups, sports activity, Tanner stages and weight trends. In addition, Spearman's correlation coefficients were computed to determine the link between UPF score in childhood and adolescence with and UPF consumption and body composition in young adults.

In adults, differences according to sociodemographic characteristics and the consumption of UPF (normally distributed) were tested using unpaired 2-tailed t-tests (comparison between 2 categories) or analysis of variance (comparison between  $\geq 3$  categories). Differences in UPF consumption between weight trends were analyzed by the non-parametric Kruskal-Wallis test. Markers of nutritional status, cardiometabolic risk factors, and diet quality were compared by tertiles of UPF consumption in adults, and p-values were obtained with analysis of variance. The level of significance was set at  $p < 0.05$ .

## Results

### *Subject characteristics*

Out of the total population of 10.750 children and adolescents, 313 subjects were identified two times in cross-sectional datasets and could thus be followed up into adulthood. For 182 subjects, complete data on body composition, socio-demographic characteristics, and diet were available. The subsample of children and adolescents was recruited from 2000 to 2010 and had a lower mean BMI-SDS (0.055 vs. 0.178,  $p = 0.05$ ) and a higher prevalence of high SES (58.6% vs. 50.4%;  $p = 0.04$ ) when compared with the total population of 10.750 children and adolescents. In adults, the BMI and SES of the subsample did not differ from the total population of 313 adults (both  $p > 0.05$ ). Table 1 shows subjects' characteristics in childhood or adolescence and adulthood stratified by sex. Sex differences were seen in children and adolescents as well as adults. In children and adolescents, FMI was higher in females compared to males, whereas body weight and FFMI were lower. In adults, males had a higher body weight, BMI, and FFMI and a lower FMI compared to females.

Table 1: Main characteristics of the study population

	Total (n 182)		Males (n 71)		Females (n 111)		<i>p</i> -value*	
	Mean	SD	Mean	SD	Mean	SD		
9 to 16-year-old	Age [years]	13.6	1.9	13.5	2.1	13.6	1.8	0.279
	Height [m]	1.63	0.12	1.67	0.15	1.61	0.10	< 0.001
	Body weight [kg]	53.4	13.0	55.8	15.6	51.8	10.9	0.035
	BMI-SDS <sup>a</sup>	0.055	0.844	0.082	0.925	0.037	0.792	0.806
	FMI [kg FM/m <sup>2</sup> ]	4.35	2.04	3.78	2.26	4.71	1.80	< 0.001
	FFMI [kg FFM/ m <sup>2</sup> ]	15.38	1.64	15.94	1.87	15.03	1.36	< 0.001
23 to 30-year-old	Age [years]	26.7	2.2	27.0	2.3	26.5	2.1	0.175
	Height [m]	1.75	0.10	1.84	0.06	1.69	0.06	< 0.001
	Body weight [kg]	70.8	15.0	81.7	14.2	63.8	10.7	< 0.001
	BMI [kg/m <sup>2</sup> ]	23.1	3.7	24.2	3.9	22.4	3.4	< 0.001
	FMI [kg FM/m <sup>2</sup> ]	6.24	3.04	5.31	3.25	6.84	2.75	< 0.001
	FFMI [kg FFM/ m <sup>2</sup> ]	16.85	2.19	18.92	1.75	15.53	1.19	< 0.001

SD, standard deviation; FMI, fat mass index; FFMI, fat free mass index; <sup>a</sup>according to Kromeyer-Hauschild et al. 2001; \*significant differences between sex by Mann-Whitney U-test;  $p < 0.05$ .

#### Estimation of UPF consumption

During childhood and adolescence, the median UPF score was 22 points with an interquartile range of 15 to 27 points. Since the maximal score was 84, the data indicate an overall low UPF-based dietary pattern. In contrast, in adults UPF consumption (NOVA 4) accounted for 46.4% of the daily energy intake (males: 48.3% energy from UPF; females: 45.2% energy from UPF). The proportion of UPF of total energy intake varied considerably between subjects, ranging between 5.0% and 92.6%. To ascertain whether there is a correlation between adherence to a UPF-based dietary pattern in childhood and adolescence and UPF consumption in young adulthood, the UPF score in children and adolescents was correlated with the UPF consumption as energy% in adults. A significant correlation was observed only in the subgroup of females ( $r = 0.272$ ;  $p = 0.004$ ), but not in males ( $r = -0.125$ ;  $p = 0.3$ ).

#### Association between UPF consumption, weight trends, and body composition

The longitudinal analysis showed that over the median follow-up time of 13.3 years (IQR: 11.2-15.0), the prevalence of overweight increased from 8.2% during childhood and adolescence to 26.9% at the age of young adults (Fig. 1). 73.3% of the subjects who were overweight during childhood or

adolescence remained overweight in adulthood, indicating a high persistence of overweight. The increase in the prevalence was explained by the low remission of 26.7%, along with a relatively high incidence of 22.2% over the follow-up time.

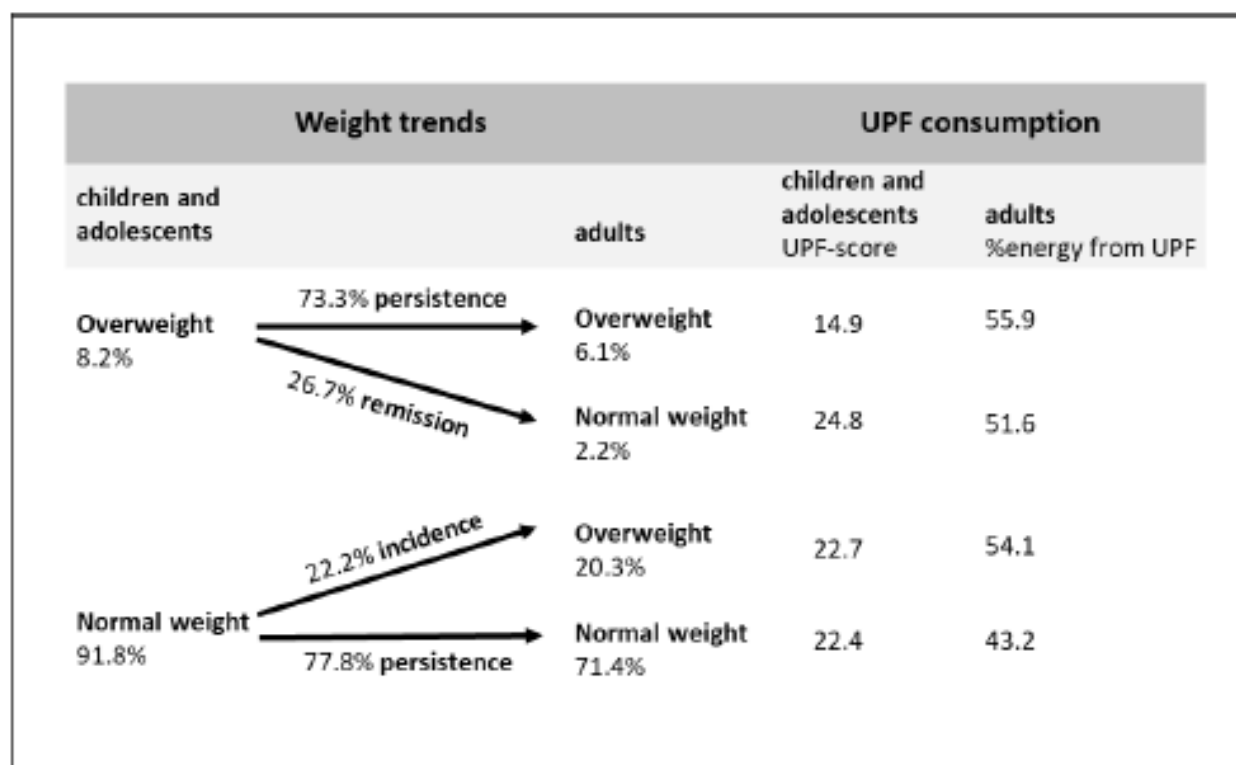


Fig 1. Weight trends from children and adolescents to young adults and related UPF consumption

Based on the dietary data assessed in childhood and adolescence, both boys and girls showed a clear inverse association between UPF score and BMI-SDS (males:  $r = -0.301$ ,  $p = 0.01$ ; females:  $r = -0.315$ ,  $p < 0.001$ ) and FMI (males:  $r = -0.376$ ,  $p = 0.001$ ; females:  $r = -0.282$ ,  $p = 0.003$ ), and the longitudinal association of UPF score during childhood and adolescents with body composition in adulthood was not significant. Subjects who were persistently overweight had a lower UPF score during childhood or adolescence compared to subjects with persistent normal weight (14.9 vs. 22.4;  $p = 0.03$ ). In addition, there was no association between UPF score and sports activity as well as no significant differences in UPF score between SES groups and Tanner stages during childhood and adolescence (all  $p > 0.05$ ).

Based on the dietary data assessed in adults, the mean UPF consumption accounted for a larger proportion of daily energy intake in subjects who became overweight (incidence) than in those with persistent normal weight (54.1 ±18.2% vs 43.2 ±19.4% energy from UPF;  $p = 0.03$ ).

*Association between UPF consumption and health outcomes and diet quality in young adults*

Table 2 shows the mean percentage of total energy intake from UPF in young adults according to sociodemographic characteristics. A larger contribution of UPF to the diet was found in subjects with overweight (BMI: 25-30 kg/m<sup>2</sup>) compared to subjects with normal weight (BMI: < 25 kg/m<sup>2</sup>), whereas there were no differences in UPF consumption between sexes, SES groups, income level, and smoking status. In addition, UPF consumption did not differ between different levels of physical activity (PAL 1.4: 47.5 ±19.6% energy from UPF; PAL 1.6: 45.3 ±19.7% energy from UPF; PAL 1.8: 45.6 ±19.0% energy from UPF; PAL 2.0: 46.0 ±19.0% energy from UPF,  $p = 0.916$ ).

**Table 2: Mean percentage of ultra-processed food in the diet according to sociodemographic characteristics of the young adults at follow-up**

	No.	Ultra-processed food in the diet [%]		
	%	Mean	SD	<i>p-value*</i>
<b>Sex</b>				
male	39.0	48.3	20.8	0.328
female	61.0	45.2	18.6	
<b>BMI</b>				
< 25 kg/m <sup>2</sup>	73.6	43.5 <sup>a</sup>	19.0	0.003
25-30 kg/m <sup>2</sup>	20.9	54.3 <sup>b</sup>	19.4	
>30 kg/m <sup>2</sup>	5.5	55.2 <sup>a,b</sup>	16.0	
<b>SES (defined by educational level)</b>				
high	82.4	45.0	19.1	0.125
middle	15.9	51.5	20.5	
low	1.1	62.9	17.0	
<b>Income</b>				
<1000 €	24.7	46.5	18.7	0.987
1000 – 2000 €	30.2	46.6	21.5	
>2000 €	45.1	46.1	18.7	
<b>Smoking status</b>				
Yes/Sometimes	14.8	48.5	18.2	0.503
No	84.6	45.8	19.6	

SES, socioeconomic status; \**p*-values were obtained with unpaired 2-tailed *t*-tests (comparison between 2 categories) or analysis of variance (comparison between 3 categories); <sup>a,b</sup> means not sharing a common superscript letter are significantly different, *p* < 0.05.

Sex-specific tertiles of UPF consumption were calculated in order to analyze the associations between UPF consumption and body composition as well as cardiometabolic risk factors (Table 3, males: tertile 1 (T1): 5.0 – 38.5% energy from UPF; tertile 2 (T2): 38.5 – 58.4% energy from UPF; tertile 3 (T3): 58.4 – 92.6% energy from UPF; females: T1: 6.2 – 36.4% energy from UPF; T2: 36.4 – 53.8% energy from UPF; T3: 53.8 – 86.8% energy from UPF). In the subgroup of males, the highest tertile of UPF consumption had a higher body weight, BMI, and FMI when compared with the lowest tertile of UPF intake. No differences in cardiometabolic risk factors were observed across tertiles of UPF consumption in both sexes.

**Table 3:** Body composition and cardiometabolic risk factors according to tertiles of ultra-processed food consumption in young adults

	Males						Females							
	Tertiles of UPF intake			Tertiles of UPF intake			Tertiles of UPF intake			Tertiles of UPF intake				
	T1	T2	T3	T1	T2	T3	T1	T2	T3	T1	T2	T3	p-value*	
<b>Body composition<sup>a</sup></b>	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD		
Body weight [kg]	75.0 <sup>a</sup>	8.9	81.6 <sup>a,b</sup>	16.3	87.2 <sup>b</sup>	14.5	0.023	63.0	8.7	64.1	10.7	64.2	12.7	0.887
BMI [kg/m <sup>2</sup> ]	22.8 <sup>a</sup>	2.2	24.3 <sup>a,b</sup>	4.8	25.5 <sup>b</sup>	3.8	0.051	21.9	3.0	22.6	2.8	22.7	4.2	0.616
FMI [kg FM/m <sup>2</sup> ]	3.81 <sup>a</sup>	2.16	5.59 <sup>b</sup>	3.77	6.46 <sup>b</sup>	3.11	0.015	6.33	2.15	6.78	2.32	7.41	3.54	0.239
FFMI [kg FFM/m <sup>2</sup> ]	18.96	1.76	18.74	1.66	19.05	1.89	0.829	15.59	1.25	15.81	1.05	15.19	1.22	0.071
<b>Cardiometabolic risk factors<sup>a,b</sup></b>	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD		
CRP [mg/dl] <sup>###</sup>	0.54	0.51	0.86	0.76	0.99	0.68	0.076	0.72	0.64	0.86	0.73	0.80	0.65	0.731
Glucose [mg/dl]	89.8	6.9	91.9	6.8	89.7	8.0	0.501	85.0	6.6	86.5	9.2	87.9	6.7	0.290
Insulin [mU/dl]	6.6	2.4	8.7	5.0	9.5	6.4	0.123	7.6	3.3	11.6	24.1	8.7	3.9	0.464
Cholesterol [mg/dl]	171.9	37.6	161.8	28.3	161.6	25.4	0.516	184.2	40.7	173.6	32.0	178.6	38.7	0.489
HDL [mg/dl]	50.8	11.4	49.8	8.6	48.6	13.4	0.800	62.77	11.2	65.0	14.4	63.1	11.5	0.724
LDL [mg/dl]	113.6	29.7	105.2	22.8	105.8	19.9	0.515	114.5	31.2	104.7	23.6	110.8	30.2	0.349
Triglycerides [mg/dl]	87.4	40.1	81.9	43.7	98.7	59.5	0.437	83.1	34.3	73.0	29.0	79.0	31.6	0.397

Males: T1, tertile 1: 5.0 – 38.5% energy from UPF; T2, tertile 2: 38.5 – 58.4% energy from UPF; T3, tertile 3: 58.4 – 92.6% energy from UPF; Females: T1, tertile 1: 6.2 – 36.4% energy from UPF; T2, tertile 2: 36.4 – 53.8% energy from UPF; T3, tertile 3: 53.8 – 86.8% energy from UPF; CRP, c-reactive protein; FMI, fat mass index; FFM, fat free mass index; <sup>#</sup> n 182 (71 males, 111 females); <sup>##</sup> n 179 (71 males, 108 females); <sup>###</sup> n 151 (66 males, 85 females); \* p-values were obtained with analysis of variance; <sup>a,b</sup> means not sharing a common superscript letter are significantly different; p < 0.05.

Combined tertiles of UPF consumption for males and females were calculated in order to analyze the association between UPF consumption and aspects of diet quality (T1: 5.0 – 37.5% energy from UPF; T2: 37.5 – 54.9% energy from UPF; T3: 54.9 – 92.6% energy from UPF). Differences in diet quality between these tertiles of UPF consumption are shown in Table 4. Adults in the third tertile of UPF consumption had a lower intake of fiber and salt and consumed more energy-dense foods when compared with the first tertile.

**Table 4: Nutrient intake indicators according to tertiles of ultra-processed food consumption in young adults**

	Tertiles of UPF intake						<i>p-value*</i>
	T1		T2		T3		
	Mean	SD	Mean	SD	Mean	SD	
Energy intake [kcal]	2,005	524	2,180	674	2,253	586	0.067
Energy density [kcal/g]	2.07 <sup>a</sup>	0.38	2.18 <sup>a,b</sup>	0.42	2.26 <sup>b</sup>	0.48	0.044
Protein [energy%]	16.0	4.6	15.8	3.7	15.2	5.2	0.556
Fat [energy%]	35.9	8.6	35.9	7.7	36.6	7.7	0.867
SFA [energy%]	14.7	5.2	15.2	4.3	16.0	4.3	0.307
MUFAs [energy%]	11.2	4.5	10.5	4.0	10.0	4.0	0.252
PUFAs [energy%]	5.1	3.1	5.3	3.5	4.1	2.1	0.072
Carbohydrates [energy%]	43.8	9.1	44.2	7.5	45.6	8.7	0.490
Total sugar [energy%]	16.5	5.4	17.3	6.1	16.7	7.6	0.721
Total sugar [g/d]	80.9	29.3	95.0	51.5	93.2	45.5	0.079
Fiber [g/d]	28.3 <sup>a</sup>	21.1	22.9 <sup>b</sup>	8.5	18.6 <sup>c</sup>	7.0	<0.001
Salt [g/d]	4.2 <sup>a</sup>	1.9	5.6 <sup>b</sup>	3.0	7.4 <sup>c</sup>	2.8	<0.001

T1, tertile 1: 5.0 – 37.5% energy from UPF; T2, tertile 2: 37.5 – 54.9% energy from UPF; T3, tertile 3: 54.9 – 92.6% energy from UPF; SFA, saturated fatty acids; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids; \*p-values were obtained with analysis of variance; <sup>a,b</sup> means not sharing a common superscript letter are significantly different; p < 0.05.

In the subgroup of females, a higher UPF intake was also associated with a higher intake of energy (T1: 1,780 ±364 vs. T3: 2,093 ±524 kcal/d; p = 0.04) and saturated fatty acids (T2: 14.3 ±4.3 vs. T3: 16.9 ±4.4; p = 0.046). There was no discrepancy in the results for the subgroup of males when compared with the whole group of males and females combined. While there was a positive correlation between UPF and sugar-sweetened beverages (SSB) consumption (r = 0.247; p = 0.001), no association was found between SSB consumption and body composition

## Discussion

There are four key findings of the present research. First, the UPF-based dietary pattern in children and adolescents was low and even showed an inverse association with BMI-SDS and FMI. Longitudinal analysis indicated that a UPF-based dietary pattern in childhood and adolescence was correlated with the UPF consumption in adulthood among females but not males, accounting for nearly 50% of daily energy intake in young adults. In addition, high UPF consumption in young adults was associated with both prevalence and incidence of overweight and correlated with markers of poor diet quality like lower intake of fiber and higher intake of salt and energy-dense food.

### *UPF consumption in children and adolescents and its impact on weight trends*

Our data showed a low UPF-based dietary pattern during childhood and adolescence. Several factors may explain this finding. Firstly, our data set for children and adolescents was collected between 2000 and 2010, when UPF sales were still expanding.<sup>25</sup> Over the last decades, UPF products have gained dominance in the global food system,<sup>5</sup> with children and adolescents identified as the largest consumer group of these products.<sup>13</sup> Contrary to our results, previous studies in Australia, the United Kingdom, and the United States found that UPF consumption accounted for a significant proportion of caloric intake in children and adolescents, ranging from 47% to 68%.<sup>13</sup> In high-income countries, the overall sales of UPF are plateauing at high levels, whereas some food groups like snack foods and sodas still increased in the last years.<sup>26</sup> This rise may be partially driven by their lower per-calorie costs, making them more affordable than non-UPF products, especially for low-income households.<sup>27</sup> The UPF-based dietary pattern in children and adolescents of the present study may also be explained by the lower BMI and the higher prevalence of high SES in subjects who were volunteering for follow-up examinations compared to the baseline population of KOPS (see results). Previous studies have shown that healthy diets, mainly composed of non-UPF, have become increasingly more expensive,<sup>28</sup> and even in Germany, healthy diets are hardly affordable for low-income households.<sup>29</sup> People with a low SES tend to shop more at low-cost stores and have increased access to unhealthy food.<sup>30</sup> In addition, UPF advertising is more common in low compared to higher SES areas.<sup>31</sup>

We found an unexpected inverse association between UPF score and BMI-SDS or FMI in children and adolescents, as well as a lower score of UPF consumption during childhood and adolescence in subjects who were persistent overweight compared to subjects with persistent normal weight. These findings are in line with the results from a cross-sectional study by Viola et al. as well as a prospective study by Cunha et al. that both showed reversed associations between UPF consumption and BMI in

adolescents.<sup>32,33</sup> The results from Cunha et al. may be explained by the fact that adolescents in the highest quartile of UPF consumption had the greatest level of physical activity.<sup>33</sup> However, we did not find an association between UPF score and sports activity in our study, but we cannot exclude the possibility of underreporting regarding sports activity. In addition, as participation in sports was the sole measure of physical activity, it is possible that our findings also underestimate the actual physical activity levels due to the omission of leisure time activity. In other cross-sectional studies that found an inverse association between energy intake and BMI, the direction of the association changed after controlling for underreporting.<sup>34</sup> Unfortunately, our FFQ did not allow us to quantify energy intake and, therefore, exclude underreporters in children and adolescents. A recent systematic review found limited and heterogeneous evidence on the association between UPF consumption and overweight or fat mass in children and adolescents.<sup>35</sup> The authors concluded that persistent UPF consumption over time is needed to impact body composition of children and adolescents.

*Associations between UPF consumption and overweight, as well as markers of poor diet quality in young adults*

In our study, UPF consumption in adults is accounting for almost 50% of daily energy intake. This finding is in line with other studies showing an average of 38 – 46% of total energy intake from UPF in German adults.<sup>36,37</sup> An increase in UPF consumption over time can be attributed to several factors, including a high supply of UPF in today's food supply.<sup>38</sup> In addition, UPF products are easily accessible and require little to no preparation, making them an integral part of everyday life. The growth in economic prosperity, increasing urbanization, and a rising number of single households have further contributed to the increased UPF consumption.<sup>39</sup> Transitioning from childhood and adolescence to adulthood may exacerbate these factors because it can lead to adverse lifestyle changes.<sup>40</sup> Key life transitions during this period, such as leaving the parental home, starting further education or paid employment, and forming partner relationships, contribute to behaviors like preferring snacks over meals and consuming meals not at home.<sup>40,41</sup> A higher prevalence of media use combined with increased exposure to advertising for low nutritional quality and energy-dense foods makes young adults more vulnerable to UPF exposure.<sup>35</sup>

Regarding associations between UPF consumption and overweight in adults, our results (Table 2) align with numerous cross-sectional as well as prospective cohort studies that have also reported similar associations between UPF and increased risk for overweight (for review, see<sup>15</sup>). The only controlled randomized cross-over trial has shown that a high UPF diet led to an increase in ad libitum

energy intake and weight gain compared to an unprocessed diet matched for overall presented calories, carbohydrate, sugar, fat, sodium, energy density glycemic load, and fiber (soluble fiber provided in a drink with the UPF diet).<sup>42</sup>

Many studies have found associations between UPF consumption and various non-communicable diseases (NCDs) such as hypertension, coronary heart disease, metabolic syndrome, and type 2 diabetes (for review, see<sup>43</sup>). Possibly due to the young age of our healthy study population, we did not find any correlation between UPF consumption and cardiometabolic risk factors (Table 3).

Numerous studies suggested that poor nutritional quality, like a higher energy density and content of saturated fatty acids, salt, and sugar, as well as lower amounts of fiber, protein, and micronutrients in UPF, may contribute to adverse health effects.<sup>43</sup> We also found that a higher UPF consumption was associated with a lower fiber intake and a higher intake of salt and energy-dense foods (Table 4). This finding may partly explain the higher UPF consumption in higher BMI groups (Table 2). Poor carbohydrate quality with a low fiber intake may impair satiety, presumably by a higher eating rate due to a higher energy density combined with a lower chewing frequency (chews per bite), leading to lower satiation as well as lower fermentation to short-chain fatty acids in the colon.<sup>44</sup> In addition, high energy density<sup>45</sup> and hyper-palatability of UPF (e.g., by a higher salt content)<sup>46</sup> can disrupt the body's ability to regulate energy balance, leading to overconsumption. The lack of a correlation between the consumption of SSBs (classified as UPF) and body composition indicates that the observed associations between UPF consumption and overweight are unlikely to be explained by the consumption of the SSB subgroup alone.

Our findings regarding indicators of poor diet quality with high consumption of UPF are already considered in the nutritional profile-based Nutri-Score. This scoring system incorporates various indicators that assess the overall nutritional quality of a product, providing consumers with information when a given food contains an excessive amount of nutrients that should be consumed in lower quantities.<sup>47</sup> However, it has been shown that even after accounting for energy intake or nutritional quality, the associations between UPF consumption and health outcomes persist.<sup>48</sup> This is in line with the observation made in a large Italian population cohort (n = 22,895) that analyzed the association between mortality risk and two different food dimensions: nutritional quality (assessed by the Nutri-Score) and the degree of food processing (assessed by NOVA).<sup>49</sup> The study showed that UPF intake, remained associated with mortality even after the poor nutritional quality of the diet was accounted for.<sup>49</sup> Additional mechanisms that may explain the adverse effects of food processing are

changes in food matrix and texture, contaminants from processing or packaging, as well as food additives and other industrial ingredients (for review, see<sup>43</sup>). However, dietary assessment using FFQ or 24h-recall did not allow for analysis of these aspects of food processing that are not covered by the Nutri-Score. Such limitations may be overcome by following the recent recommendations of best practices for applying the NOVA food classification system, including brand names of packed foods, location of meal preparation and the information if foods were purchased ready-to-eat.<sup>50</sup>

#### *Study limitations*

It should be noted that the present study is not without limitations. Dietary assessment was conducted using a FFQ in childhood and adolescence, and a 24-hour recall in adulthood. The discrepancy in UPF consumption between adults and children/adolescents may therefore be attributed to a less precise assessment of UPF consumption by the FFQ. The FFQ design precluded differentiation of UPF consumption in excess of one portion per day, thereby limiting the estimation of a UPF consumption. This may have resulted in an underestimation of UPF intake among children and adolescents. Therefore, the UPF score merely serves as a marker for adherence to a UPF-based dietary pattern in childhood and adolescences. Furthermore, the present study does not consider the timing of dietary assessment, which may have resulted in a seasonal discrepancy in UPF consumption between baseline and follow-up.

In conclusion, a UPF-based dietary pattern was low during childhood and adolescence and correlated with the UPF consumption in adulthood among females. High UPF consumption in adults was associated with both prevalence and incidence of overweight and aspects of lower diet quality, including a lower fiber intake and a higher intake of salt and energy-dense foods.

**Ethical Standards Disclosure:** This study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving research study participants were approved by the local ethical committee of the Medical Faculty of Kiel University (Kiel, Germany). Written informed consent was obtained from the subjects themselves or their parents.

**Conflict of interest statement:** The authors have no conflicts of interest to declare.

**Authorship:** SF and ABW wrote the manuscript; SF, SPD, AS acquired data; SF did the statistical analysis; SF, ABW, MJM, SPD did the interpretation of the data. All authors have read and agreed to the final version of the manuscript.

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## Chapter IV

### **Contribution of ultra-processed food to nutritional quality and nutritional status in first-year students with different plant-forward eating patterns**

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**Contribution of ultra-processed food to nutritional quality and nutritional status in first-year students with different plant-forward eating patterns**

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**Abstract**

The health benefits of a plant-based diet may be outweighed by an increased consumption of ultra-processed foods (UPF) and plant-based alternatives. Diet quality and nutritional status were assessed in 142 adults with different plant-forward eating patterns ( $20 \pm 1.6$  years, BMI  $21.9 \pm 3.1$  kg/m<sup>2</sup>, 83% female, 22.5% vegans, 46.5% vegetarians, 31% omnivores). Qualitative aspects of the food were compared between NOVA categories as well as between consumed plant-based alternatives and animal products. Irrespective of the diet, UPF contributed to 49% of daily energy intake. The prevalence of low holotranscobalamin and ferritin levels was similar between diet groups. Vitamin B12, folate, iron, zinc and calcium were on average consumed below the recommended intake, especially in vegans and vegetarians. UPF exhibited a lower content of protein, fiber, vitamin B2, vitamin B12, folate, zinc and calcium compared to processed foods (all  $p < 0.001$ ). Plant-based alternatives contained more fiber and less saturated fatty acids whereas the content of protein and micronutrients was lower compared with animal products (all  $p < 0.05$ ). In conclusion, UPF consumption contributes to the insufficient intake of many micronutrients by young adults. This is further aggravated by plant-forward eating patterns including the consumption of plant-based alternatives.

## Introduction

Certain life transitions, such as moving from home to university, can alter established dietary patterns [1]. This can lead to changes in food intake that are mostly unfavorable, such as low consumption of fruits and vegetables and a higher intake of sugar and alcohol [2,3]. The negative shift in dietary behavior due to newfound independence accompanied by exposition to various new experiences [4] may explain the frequently observed weight gain during the first year at university (for review, see [5]). In addition, factors such as time constraints and financial limitations [3], as well as a lack of experience in meal planning and preparation [6], contribute to the adoption of unhealthy eating habits, often characterized by the consumption of ultra-processed foods (UPF).

Today, UPF products constitute a major part of the food supply in retail [7] and fast-food or takeout restaurants [8]. These products are designed to be ready-to-eat or ready-to-heat, hyper-palatable, and are affordable for most people [9]. The trend towards a higher UPF consumption was shown to be aggravated in a plant-based diet because of increased consumption of plant-based alternatives that facilitate the maintenance of traditional eating habits [10]. In line with this observation, the sales of plant-based alternatives increased rapidly during the last years [11]. In Germany, about 3% of the adult population are vegan, 9% are vegetarian, and 41% report following a flexitarian diet [12]. A plant-based diet is thereby particularly popular among younger people with a high educational level [12] and environmental consciousness [13] due to ethical considerations and health reasons (for review, see [14]). However, the health benefits of a plant-based diet were outweighed by an unhealthy, more processed dietary pattern [15] that is usually characterized by a higher glycemic load and index, added sugar, and lower levels of dietary fiber, unsaturated fats, micronutrients, and antioxidants [15]. The impact of consumed plant-based alternatives on diet quality is unclear, given the significant variation in nutritional quality among these products [16,17]. Health assessment of contemporary plant-based diets is therefore important in order to differentiate recommendations for these diets as part of a sustainable diet transformation.

Thus, the present study aims to identify the contribution of UPF and the subgroup of plant-based meat and dairy alternatives to qualitative aspects of the diet (i.e., energy and micronutrient density, intake of protein, saturated fat, sugar, and fiber) in first-year students. In addition, we investigate the association between UPF consumption and iron and vitamin B12 status in students with different plant-forward eating patterns.

## Methods

### *Study population*

The present study was conducted between November 2020 and January 2024 at the Institute of Human Nutrition and Food Science at Kiel University, Germany. The study's primary aim was to assess changes in body weight in first-year students (freshman weight gain). Therefore, we recruited only first-year students from all universities in Kiel through notice board postings and social media platforms at the beginning of their first semester. A web-based recruitment questionnaire was used to determine whether the first-year students met the inclusion criteria (first semester at university, ages between 18 and 25, vegan, vegetarian, or omnivore diet  $\geq 3$  months). Exclusion criteria were regular medication use, chronic diseases (especially bowel diseases), and electrical implants (due to the manufacturer's recommendations of bioelectrical impedance analysis). Afterwards, a personal interview was conducted at the institute to verify the information. Eligible individuals were subsequently invited for the examination visit, where body composition was examined, and blood sampling took place, followed by a 2-week period in which the diet was recorded on three consecutive days. 151 participants were examined, 142 of whom provided complete dietary records. Self-reported eating habits were used to classify participants comprising vegans, vegetarians, and omnivores. Written informed consent was obtained from each participant. The study protocol was approved by the medical ethics committee of Kiel University, Germany (AZ D 534/20) and followed the guidelines based on the 'Declaration of Helsinki'. The trial was registered at ClinicalTrials.gov as NCT04598022.

### *Body composition*

Height was determined without shoes using a stadiometer (SECA, Modell 285, Hamburg, Germany). Body weight was measured on a calibrated scale, and body composition was assessed using bioelectrical impedance analysis (mBCA 515, seca GmbH & co. kg., Hamburg, Germany), both in underwear after an overnight fast. Fat mass index (FMI) and fat-free mass index (FFMI) were calculated as fat mass or fat-free mass divided by height squared ( $\text{kg}/\text{m}^2$ ).

### *Blood sampling*

Blood samples were collected after an overnight fast ( $\geq 10$ h) between 06:30 a.m. and 10:00 a.m. Vitamin B12 status was assessed by analyzing serum holotranscobalamin (HTC) immunologically via a chemiluminescence microparticle assay. Iron status was assessed by analyzing serum ferritin using

an immunoturbidimetric method. The analysis of all blood parameters was performed in an accredited and certified laboratory (Labor Dr. Krause & Kollegen MVZ GmbH, Kiel, Germany).

#### *Lifestyle data*

A study-specific online questionnaire was used to collect sociodemographic data, including sex, age upon study participation, duration and reason for the choice of dietary pattern, smoking status, income (including the share of food expenditure), and whether they used dietary supplements (particularly vitamin B12 and iron supplements).

#### *Dietary data*

Participants self-recorded their dietary habits using dietary records for three consecutive days, including one weekend day. They were instructed to document the following information for all consumed food products and beverages: time and place of consumption (to assess out-of-home consumption), brand and product name, as well as preparation instructions. All food quantities were weighted or estimated by the participants in grams or household measures. Daily macro- and micronutrient intakes were calculated using the nutrition software PRODI<sup>®</sup> 6.11 (Nutri-Science GmbH, Freiburg, Germany). The German Nutrient Database (BLS, Bundeslebensmittelschlüssel) Version 3.02 was used to evaluate unprocessed foods such as fruit and vegetables, but also for some processed foods such as bread, cheese, and canned goods. For most processed food products, recipes based on the manufacturer's information had to be created by hand, as most were not included in the BLS. The ingredients listed in those recipes were based on information from the BLS in order to assess the nutrients of all ingredients (in particular, micronutrients). In case of incomplete product information, equivalent food products from the BLS were used or, if not available, comparable products from other manufacturers. Standardized recipes were developed for composite foods and dishes not described sufficiently to identify all ingredients and intake quantity. This applied to most takeaway or restaurant dishes and some homemade dishes without further details. The Dietary Reference Intake values of the German Society for Nutrition [18] were used to evaluate nutrient intake. No underreporting was observed according to Willet's criteria (>500 kcal/d for females and >800 kcal/d for males). This may be due to the exclusion of incomplete dietary records (<3 days) and the intensive support provided during the protocol phase.

### *Level of food processing*

All reported food items were categorized according to the extent and purpose of food processing following the NOVA classification system [19]. This system differentiates between four food groups: 1. unprocessed and low-processed foods, 2. culinary ingredients, 3. processed foods, and 4. ultra-processed foods (UPF). In order to minimize errors, two researchers and one dietitian conducted a consensus-based classification process based on the recommendations of Martínez-Steele et al. [20]. Therefore, a list of all consumed food products was compiled, with single-ingredient foods classified as NOVA 1 or 2. Multi-ingredient food products that were clearly industrially manufactured were assigned to NOVA 4. Accuracy of classification was improved by using available information like the brand and product name (ingredient list), the preparation method (e.g., homemade, takeaway, restaurant), or certain key phrases in the food product description (e.g., fresh, unpackaged, ready-made, instant). For any remaining uncertainty, the food product was assigned to the most likely NOVA group based on the majority of other participants' responses, findings from other studies, or else, the product was systematically assigned to the lower NOVA group. These food products were flagged for sensitivity analysis to calculate a lower and upper NOVA distribution range representing inter-rater agreement.

Qualitative aspects of the diet were determined by analyzing the contribution of each NOVA food group to the daily absolute and relative intake of energy, protein, SFA, sugar, and fiber, as well as vitamin B2, vitamin B12, folate, iron, zinc, and calcium. In order to compare qualitative aspects of consumed foods (food level) between NOVA food groups 3 and 4, the average content of macronutrients is given as the energy percentage of food, and the micronutrient content is given as 100g of food. By assessing both qualitative aspects of the diet and foods, we are able to detect if a lower nutrient content of NOVA 4 foods may be compensated by a higher intake of these products, which results in an overall sufficient nutrient intake.

### *Classification of plant-based alternatives*

Products mimicking meat or dairy were defined as plant-based alternatives. Tofu or seitan in their original form were also included in this category as they are often used as meat alternatives in Western diets. Whenever possible, the plant-based alternatives were categorized according to NOVA based on the ingredient information. If brand information was missing, meat alternatives were classified as ultra-processed [19,20]. Plant-based milk alternatives with missing brand information were assigned to NOVA 3 following the best practice approach of Martínez-Steele et al. (77% of

reported plant-based milk alternatives were not ultra-processed) [20]. Plant-based yogurt, cream, and cheese alternatives were categorized more frequently as ultra-processed, which is why NOVA 4 was chosen in cases of missing brand information.

The contribution of plant-based alternatives to qualitative aspects of the diet was calculated overall and within the different diet groups by analyzing their contribution to total dietary intake of energy, protein, SFA, sugar, and fiber, as well as vitamin B2, vitamin B12, folate, iron, zinc, and calcium. In order to compare qualitative aspects of plant-based alternative products (categorized into meat alternatives and dairy alternatives) with qualitative aspects of milk and dairy products, the average content of macronutrients is given as energy percentage of food, and the micronutrient content is given as 100 g of food.

#### *Statistical analysis*

Statistical analyses were conducted using IBM SPSS Statistics® (SPSS 28.0, Inc., Chicago, IL, USA) with the significance level set at  $p < 0.05$ . Normal distribution of data was rejected using the Kolmogorov-Smirnov test, and the data are presented as medians and interquartile ranges. Differences between diet groups regarding basal characteristics, daily intake of macro- and micronutrients, blood parameters, as well as the contribution of plant-based alternatives to qualitative aspects of the diet were examined using the Kruskal-Wallis test with the Bonferroni post-hoc test for metric variables and chi-square test with pairwise comparison for categorical variables. Daily intake of various micronutrients was compared between tertiles of UPF consumption, and p-values were obtained using the Kruskal-Wallis test with the Bonferroni post-hoc test. Spearman's correlation coefficients were computed to determine the impact of UPF consumption on BMI and FMI. To assess qualitative differences between NOVA 3 and NOVA 4 food products, an unpaired two-sided Welch t-test was conducted due to large group sizes. These data are presented as mean  $\pm$ SD. Graphs were plotted using GraphPad Prism 10.2.2 (GraphPad Prism for Windows, GraphPad Software, La Jolla, California, USA).

## **Results**

### *Characterization of the study population*

Table 1 shows the main characteristics of the participants overall and stratified into vegans, vegetarians, and omnivores. 83% of participants were female, with no differences between diet groups regarding age, percentage of smokers, or monthly expenditure on food. Omnivores

maintained their dietary habits since childhood, while vegans and vegetarians have only been eating their diet for a median of 2-3 years ( $p<0.001$ ). Vegans and vegetarians had a lower BMI ( $p=0.005$ ) and a tendency towards a lower energy intake ( $p=0.06$ ; Table 2) compared to omnivores. 60% of participants reported taking dietary supplements, with a particularly high intake among vegans, who also had a higher regular intake of vitamin B12 and iron supplements compared with vegetarians and omnivores (Table 1;  $p<0.001$ ). The three diet groups showed typical nutritional patterns, with vegans consuming less protein, less SFA, and more fiber than omnivores (Table 2). Vegans also had a lower vitamin B2 and calcium intake than vegetarians and omnivores while having the highest folate intake (all  $p<0.01$ ).

#### *Contribution of ultra-processed food to qualitative aspects of the diet*

A total of 8,626 foods (incl. beverages) were consumed over the 3-day protocol phase. According to the best practice approach from Martinez-Steele et al. [20], all foods were categorized into the four NOVA categories. UPF contributed to 49% of daily energy intake (Table 3), with 5.9% of foods that could not be assigned with certainty to NOVA categories, resulting in a lower and upper bound of 45.5 – 53.0% energy intake from UPF. UPF accounted for 46.2%, 50.5%, and 48.7% of daily energy intake in vegans, vegetarians, and omnivores, respectively ( $p=0.514$ ). Because no differences between diet groups were observed, the contribution of UPF to qualitative aspects of the diet was analyzed for all participants combined. A higher intake of UPF correlated with FMI in females ( $r=0.22$ ;  $p=0.017$ ) but not in males. There was no association between UPF intake and BMI in both sexes ( $p>0.05$ ).

Table 3 shows that UPF accounted for a larger intake of energy% of of protein, SFA, sugar, and fiber compared to NOVA 1-3. The average protein content of UPF was, however, 6% lower than in processed foods (NOVA 3;  $p<0.001$ ). Compared with NOVA 3, UPF had a 1% lower fiber and a 7% higher sugar content, whereas there were no differences in SFA content between these two NOVA categories. In addition, UPF had a higher energy density than processed foods from NOVA 3 (2.88 vs. 1.95 kcal/g;  $p<0.001$ ).

Although UPF contributed to the largest proportion of intake of critical micronutrients for plant-based diets among all NOVA categories (vitamin B2: 40%, vitamin B12: 53%, iron: 47%, zinc: 39% and calcium: 36%), on the food level, UPF contained 50% less vitamin B2, 29% less vitamin B12, 31% less zinc and 57% less calcium than processed foods per 100 g food (NOVA 3, Figure 1). On the contrary, iron content in UPF was 50% higher, primarily due to plant-based foods with high cocoa content, soy-

based products, or processed meat products. Folate intake was mainly obtained (42%) from unprocessed foods (NOVA 1), with no differences in folate content between UPF and processed foods (NOVA 3).

#### *Vitamin B12 and iron intake and status*

According to the reference value of vitamin B12 intake from the German Society for Nutrition (4 µg/d), 84% of participants had an inadequate vitamin B12 intake without considering supplement intake. Vegans had a lower vitamin B12 intake than vegetarians and omnivores ( $p < 0.001$ ; Figure 2A). Using HTC as a marker of B12 status, lower serum concentrations were observed in vegetarians than in omnivores ( $p < 0.05$ ; Figure 2B). The prevalence of low HTC levels was 27% overall, with 25% among vegans, 35% among vegetarians, and 16% among omnivores. Notably, females accounted for 97% of the HTC levels that were too low. A correlation between vitamin B12 intake and HTC levels was observed in omnivores only ( $r = 0.414$ ,  $p = 0.005$ ).

Vegans were found to have a higher iron intake (excl. supplements) than vegetarians and omnivores (Figure 2C). 38% of vegans, 53% of vegetarians, and 68% of omnivores were found to have an insufficient iron intake according to the reference value of iron intake from the German Society for Nutrition (16 mg/d in females). Based on ferritin levels, 80% of participants showed an adequate iron status, with no differences in ferritin concentrations between diet groups for both females (Figure 2D) and males (data not shown; all  $p > 0.05$ ). No correlation was found between iron intake and iron status, even when the data were stratified by sex and diet group (all  $p > 0.05$ ).

Comparing vitamin B12 and iron intake between tertiles of UPF consumption (tertile 1: 14.0%–40.8% energy from UPF; tertile 2: 40.8%–56.1% energy from UPF; tertile 3: 56.1%–86.0% energy from UPF) no differences were observed regarding iron intake ( $p > 0.05$ ). By contrast, the highest tertile of UPF consumption showed a higher intake of vitamin B12 compared to the lowest tertile (2.5 vs. 1.1 µg/d,  $p = 0.014$ ). The main sources of vitamin B12 among UPF were meat products, fortified plant-based alternatives, fortified juices, soft drinks (energy drinks), and energy/protein bars.

#### *Consumption of plant-based meat and dairy alternatives*

Plant-based alternatives were consumed by 79% of the participants, with 100% of vegans reporting daily consumption, followed by vegetarians (85%) and omnivores (55%, difference between diet groups  $p < 0.001$ ). Accordingly, plant-based alternatives accounted for a larger proportion of daily energy intake in vegans (12%) compared to vegetarians and omnivores (7% and 5% of total energy

intake,  $p < 0.001$ , Table 4). The percentage of protein and micronutrient intake from plant-based alternatives was at least as high as the percentage of energy intake from these foods. However, the percentage of SFA intake from plant-based alternatives was also higher than the energy intake from these foods. Although 44% of vitamin B12 intake was derived from plant-based alternatives in vegans, these products did not contribute to vitamin B12 supply because of the overall very low intake of vitamin B12 from fortified foods in this diet group (Figure 2).

Figure 3 compares the qualitative aspects of plant-based dairy alternatives with milk and dairy products (Figure 3A) and plant-based meat alternatives with meat and meat products (Figure 3B). More plant-based alternatives were categorized as UPF compared to animal-based products (dairy alternatives: 51%, dairy products: 13%; meat alternatives: 96%, meat products: 66%; both  $p < 0.001$ ). The energy density of consumed plant-based meat and dairy alternatives was lower than that of animal-based products (dairy alternatives and dairy products:  $1.2 \pm 1.7$  vs.  $3.0 \pm 2.2$  kcal/g; meat alternatives and meat products:  $1.7 \pm 0.7$  vs.  $2.4 \pm 0.9$  kcal/g; both  $p < 0.001$ ). Plant-based dairy alternatives contained 9% less protein, 26% less SFA, 2% less sugar, and 4% more fiber than milk and dairy products (Figure 3A). Plant-based meat alternatives contained 8% less protein, 15% less SFA, 4% more sugar, and 4% more fiber than meat and meat products (Figure 3B).

Dairy products, compared with plant-based dairy alternatives, had a higher content of all micronutrients (all  $p > 0.05$ ) except for iron, which was higher in plant-based dairy alternatives ( $p < 0.001$ ; Table 5). Plant-based meat alternatives contained more calcium, folate, and iron and less vitamin B2, vitamin B12, and zinc than meat products (all  $p < 0.001$ ). Of the plant-based alternatives consumed, 17% were fortified with micronutrients (dairy alternatives: 23%; meat alternatives: 1%), primarily with vitamin B12 (12%), with an average fortification of  $0.7 \mu\text{g}/100\text{g}$  food.

## Discussion

UPF constituted 49% of the daily energy intake, irrespective of the plant-forward eating pattern. Qualitative analysis of the diet revealed that UPF contributed to a significant portion of nutrient intake across all diet groups. However, an assessment of the qualitative aspects of the consumed foods revealed that UPF exhibited lower content of protein, fiber, vitamin B2, vitamin B12, folate, zinc, and calcium compared to processed foods (NOVA 3). The subgroup of plant-based alternatives had a lower content of SFA, a higher fiber content, and a lower energy density than consumed animal-based

products. Conversely, plant-based alternatives exhibited lower protein content and a lower content of certain micronutrients.

#### *Diet quality and nutritional status in different plant-forward eating patterns*

Vegans and vegetarians exhibited lower protein, higher fiber, and a trend towards a lower energy intake compared to omnivores (Table 2). These characteristics are consistent with those observed in previous large-scale cohort studies [21,22] and in recent data from Germany [23,24]. Overall, the total macronutrient intake was generally aligned with the recommendations of the German Society of Nutrition, while only the intake of SFA and total sugar exceeded the recommended levels [18]. Most micronutrients assessed (vitamin B12, folate, iron, zinc, and calcium) were on average consumed at levels below the recommended intake [18].

We found an equally high UPF consumption in all diet groups, while other studies have indicated that a higher avoidance of animal-based foods is associated with a higher UPF consumption [10]. Since UPF are characterized as energy-dense and nutrient-poor [19], they may aggravate the low intake of critical nutrients in vegans and vegetarians. By contrast, our data indicate a risk of undersupply with vitamin B12 in all diet groups (Figure 2A). Due to the usual supplementation practice, no significant differences were observed in HTC levels between vegans and omnivores (Figure 2B). Those results are in accordance with previous findings from Germany that also found no differences in HTC levels between vegans and omnivores [25]. However, vegetarians showed lower HTC levels, possibly because of lower supplementation rates of vitamin B12 compared to vegans. Vitamin B12 supplements were taken by 60% of all participants and 78% of vegans, which is consistent with other studies that have reported supplementation rates of 82-92% among German vegans [24–26]. Nevertheless, over 20% of vegans still lack vitamin B12 supplementation, underscoring the necessity for further education on this topic, particularly as plant-based diets continue to gain popularity across all age groups and educational levels. Notably, the prevalence of low HTC levels was similar across all diet groups and amounted to 16% even in omnivores. This unexpected finding may be attributed to a reduction in the bioavailability of vitamin B12 in UPF like processed meat products [27]. This conundrum requires further investigation, as vitamin B12 deficiency in women of childbearing age is clinically significant [28].

Even though vegans demonstrated a higher iron intake than vegetarians and omnivores (Figure 2C), the ferritin levels across the different diet groups were comparable (Figure 2D). This is likely attributed

to the reduced bioavailability of non-heme iron and inhibitors such as phytic acid and polyphenols in plant-based foods [29]. It can be reasonably inferred that iron intake should be approximately 1.8-times higher than that observed in omnivorous diets [29].

#### *Contribution of UPF to diet quality*

The lower content of protein, fiber, vitamin B2, vitamin B12, folate, zinc, and calcium of UPF compared to processed foods (Table 3, Figure 1) are supported by findings from market analyses that have shown a poorer nutritional profile of UPF compared to less processed foods [30]. Such a poor nutritional profile of UPF has been identified as a main driver of their detrimental impact on health (for review, see [31]). Although UPF account for 46% of total protein intake, the protein content of UPF is lower (13%) than that of processed foods (19%). The lower protein intake with high consumption of UPF has been shown to be associated with a higher total energy intake, while the absolute protein intake remained relatively constant [32]. The low protein content together with a low fiber and high sugar content and a higher energy density, may thus explain the elevated risk of overweight and obesity associated with a high UPF consumption [33]. The difference in the mean energy density of 2.88 kcal/g in UPF and 1.95 kcal/g in NOVA 3 foods may, however, not be relevant because the relationship between energy density and caloric intake was found to be non-linear, with consumption only increasing up to an energy density of approximately 1.5 kcal/g and slightly decreasing thereafter [34].

Our data demonstrate that UPF contain lower amounts of vitamin B2, vitamin B12, calcium, and zinc compared to processed foods (Figure 1). These results add to the finding that high UPF consumption is associated with a lower micronutrient intake [35]. The iron content was unexpectedly higher in UPF than in processed foods, presumably due to the high iron content in ultra-processed meat products and cocoa or soy-containing UPF. The latter advantage is, however, compensated by a reduced bioavailability of non-heme iron in plant-based products [29]. Accordingly, the substitution of UPF with less processed foods is expected to result in an enhancement of overall diet quality. Replacing UPF with less processed alternatives was predicted to reduce health implications due to the lower nutritional quality of UPF [7]. The authors therefore concluded that the availability of information on the degree of processing, which is currently lacking for consumers, could enhance population health.

*Contribution of plant-based alternatives to diet quality*

In all diet groups, plant-based alternatives were consumed, with the highest prevalence among vegans, who consumed these products on a daily basis (Table 4). Despite comprising merely 12% of energy intake among vegans, these products provided 18% of protein intake but also 24% of SFA intake. Not all plant-based alternatives were classified as UPF (51% of dairy and 89% of meat alternatives), which is noteworthy, given the observed association between plant-based non-UPF and reduced cardiovascular risk, and the observed positive association between plant-based UPF and cardiovascular risk [16]. The underlying mechanisms for the adverse effects of plant-based UPF remain unclear. The lower SFA content and lower energy density of plant-based alternatives (Figure 3) compared to animal products are unlikely to be the cause as they even represent an advantage of these products [36,37]. The higher fiber content in plant-based alternatives may also be perceived as favorable but the quantities are mostly inadequate to qualify as a substantial source of fiber [38]. For example, dairy alternatives contained only 0.9g of fiber per 100g. The dietary fibers employed for technological purposes in UPF are often synthetic or isolated, which may not provide the same micronutrients or health benefits as those derived from whole foods [39]. The impact of these fibers on a food matrix that may lower the eating rate and thus energy intake remains uncertain [40]. A disadvantage of plant-based alternatives is the lower protein content compared with animal-based products (Figure 3). Although protein intake was adequate in all diet groups, a higher protein intake could promote satiety and thus prevent overconsumption (for review, see [41]).

In terms of micronutrients, plant-based dairy alternatives were generally less adequate than plant-based meat alternatives because they contain lower amounts of nutrients compared to animal-based dairy products, except for iron. By contrast, plant-based meat alternatives showed a higher content of iron, calcium, and folate than the consumed meat products (Table 5). These findings are consistent with previous research conducted in Germany, suggesting that plant-based meat alternatives could contribute to daily iron requirements [42]. In addition, the plant-based meat alternatives, rather than the plant-based dairy alternatives, serve as a source of calcium. This is presumably attributed to calcium-rich ingredients derived from soy and other legumes. In light of the low calcium intake in all diet groups (Table 2) and the growing consumption of these products in Germany [11], the low calcium content represents a significant public health concern, particularly among vulnerable populations, including adolescents and adults who need to increase their peak bone mass. Fortification is, therefore, a good option for making these plant-based alternatives a viable source of

not only calcium but also vitamin B12. However, other authors take a critical view of UPF fortification, making the food appear more positive [43].

#### *Strength and Limitations*

Accurate dietary assessment was obtained by following the best practice approach for NOVA classification [20] with a sensitivity analysis for quantification of uncertainty to increase the comparability of the estimates (see results). A key strength of our study is the thorough documentation of the brands of consumed foods, enabling detailed analysis of ingredients and therefore the classification according to NOVA. However, due to missing information on the recipes, the amounts of ingredients were adjusted to match the nutritional information on the product. For missing information on novel ingredients (e.g., bamboo fiber) that were not included in the BLS database assumptions based on existing literature were used.

In conclusion, our findings indicate an insufficient intake of many micronutrients by young adults in Germany. The lower content of micronutrients in UPF is a contributing factor to this phenomenon. Substituting UPF with processed foods could, therefore, contribute to an improvement in diet quality. The problem of insufficient micronutrient intake is further aggravated by a plant-forward eating pattern. This is also reflected in the lower micronutrient content of plant-based alternatives. A fortification of plant-based milk alternatives could, however, contribute to an improvement in diet quality.

**Data Availability:**

The data supporting this study's findings are not publicly available due to the data privacy statement in the subject information form and are available from the corresponding author A.B.-W. upon reasonable request.

**Competing interests:**

The authors declare no competing interests.

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**Author Contributions:**

A.B.-W designed research; A.B.-W., S.F., M.W., and F.A.H. conducted research; S.F. analyzed data; A.B.-W. and S.F. wrote the paper and had primary responsibility for the final content; A.B.-W, S.F., M.W., F.A.H., and M.J.M. discussed the data. All authors read and approved the final manuscript.

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## Tables

Table 1: Main characteristics of the study population

	Total (n = 142)	Vegans (n = 32)	Vegetarians (n = 66)	Omnivores (n = 44)	<i>p-value*</i>
Males, n (%)	24 (16.9)	3 (9.4)	12 (18.2)	9 (20.5)	0.414
Females, n (%)	118 (83.1)	29 (90.6)	54 (81.2)	35 (79.5)	
Age, years	20 (19-21)	20 (19-21)	20 (19-20)	20 (19-21)	0.511
BMI, kg/m <sup>2</sup>	22 (20.9-23.4)	20.6 <sup>a</sup> (18.9-23.0)	21.3 <sup>a</sup> (20-22)	22.2 <sup>b</sup> (21-24.3)	0.005
FMI, kg FM/m <sup>2</sup>	f: 6.0 (5.0-7.1) m: 2.5 (2.1-4.1)	f: 5.3 (4.6-7.1) m: 3.1 (1.3-4.8)	f: 5.9 (5.1-7.0) m: 2.5 (1.9-4.3)	f: 6.5 (5.6-8.1) m: 2.5 (2.3-3.8)	f: 0.112 m: 0.942
Cigarette smoker, n (%)	20 (14.1)	6 (18.8)	6 (9.1)	8 (18.2)	0.280
Food Expenditure, €/month	150 (100-200)	160 (100-250)	150 (100-200)	140 (90-213)	0.268
Adherence to diet, years	5 (2-19)	2 <sup>a</sup> (1-3.5)	3 <sup>b</sup> (2-7)	20 <sup>c</sup> (19-21)	<0.001
Consumption of dietary supplements, n (%)	85 (59.9)	28 <sup>a</sup> (87.5)	34 <sup>b</sup> (51.5)	23 <sup>b</sup> (52.3)	0.001
Consumption of vitamin B12 supplements, n (%)	44 (31.0)	25 <sup>a</sup> (78.1)	15 <sup>b</sup> (22.7)	4 <sup>b</sup> (9.1)	<0.001
Consumption of iron supplements, n (%)	25 (17.6)	12 <sup>a</sup> (37.5)	12 <sup>b</sup> (18.2)	1 <sup>c</sup> (2.3)	<0.001

Data presented as median (interquartile range) unless otherwise stated; \* *p*-values refer to differences between diet groups using chi-square with pairwise comparison and Kruskal-Wallis test with Bonferroni post-hoc test; <sup>a,b</sup> diet groups not sharing a common superscript letter are significantly different, *p* < 0.05; BMI, body mass index; f, female; m, male.

**Table 2:** Daily dietary intake of macro-, micronutrients and salt in vegans, vegetarians and omnivores reported in 3-d-dietary protocols (without supplements)

	Total (n = 142)	Vegans (n = 32)	Vegetarians (n = 66)	Omnivores (n = 44)	p-value*
Energy [kcal]	2050 (1722-2381)	1842 (1525-2245)	2104 (1829-2440)	2028 (1729-2442)	0.063
Protein [E%]	12.8 (11.5-15.3)	11.9 <sup>a</sup> (9.6-14.8)	12.5 <sup>a</sup> (11.1-14.2)	14.7 <sup>b</sup> (12.9-16.9)	<0.001
Fat [E%]	34.0 (29.5-39.2)	30.0 <sup>a</sup> (26.0-35.8)	35.5 <sup>b</sup> (30.8-40.1)	33.8 <sup>ab</sup> (29.7-40.1)	0.013
SFA [E%]	12.2 (9.1-15.7)	8.6 <sup>a</sup> (6.3-10.5)	12.7 <sup>b</sup> (9.9-16.9)	14.5 <sup>b</sup> (10.6-16.1)	<0.001
MUFAs [E%]	11.7 (9.8-13.4)	11.1 (9.2-12.7)	12.2 (10.7-13.6)	11.3 (9.5-14.2)	0.205
PUFAs [E%]	6.4 (5.2-8.4)	8.1 <sup>a</sup> (5.7-10.1)	6.8 <sup>ab</sup> (5.3-8.5)	5.8 <sup>b</sup> (4.8-6.7)	<0.001
Carbohydrates [E%]	46.8 (43.0-50.6)	49.6 <sup>a</sup> (46.6-51.7)	46.0 <sup>ab</sup> (43.2-49.5)	45.1 <sup>b</sup> (40.2-48.7)	0.016
Total sugar [E%]	15.6 (12.3-20.1)	16.1 (14.1-20.3)	15.4 (12.2-20.5)	15.4 (11.9-19.5)	0.593
Fiber [E%]	2.8 (2.2-3.6)	3.9 <sup>a</sup> (3.1-4.9)	2.8 <sup>b</sup> (2.2-3.4)	2.3 <sup>c</sup> (1.9-2.8)	<0.001
Salt [g/d]	5.2 (3.6-6.7)	5.0 (3.3-6.1)	5.4 (3.5-6.7)	5.2 (3.9-7.5)	0.320
Vitamin B2 [mg/d]	1.1 (0.9-1.5)	0.8 <sup>a</sup> (0.7-1.1)	1.2 <sup>b</sup> (0.9-1.5)	1.2 <sup>b</sup> (0.9-1.7)	<0.001
Folate [µg/d]	276.7 (211.8-369.2)	364.5 <sup>a</sup> (247.7-456.0)	288.7 <sup>ab</sup> (217.9-346.6)	227.2 <sup>b</sup> (174.8-316.4)	0.001
Zinc [mg/d]	9.8 (7.8-12.1)	8.9 (6.5-11.3)	9.8 (7.9-12.0)	10.6 (8.6-12.5)	0.086
Calcium [mg/d]	771 (558-1050)	552 <sup>a</sup> (484-681)	914 <sup>b</sup> (655-1151)	791 <sup>b</sup> (553-1064)	<0.001

Data presented as median (interquartile range); \* p-values refer to differences between diet groups using Kruskal-Wallis test with Bonferroni post-hoc test; <sup>ab</sup> diet groups not sharing a common superscript letter are significantly different, p < 0.05; E%, energy percent; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids; SFA, saturated fatty acids.

**Table 3:** Contribution of NOVA food groups to qualitative aspects of the diet (protein, saturated fatty acids, sugar, and fiber) in first-year students ( $n = 142$ ), and mean protein, saturated fatty acids, sugar, and fiber content of consumed foods according to each NOVA group

	Mean energy intake		Mean protein intake		Mean saturated fat (SFA) intake		Mean sugar intake		Mean fiber intake					
	kcal/d	E%	g/d	%	g/d	%	g/d	%	g/d	%				
											Mean protein content [E% of food]	Mean SFA content [E% of food]	Mean sugar content [E% of food]	Mean fiber content [E% of food]
<b>NOVA 1</b> ( $n = 4100$ )	519 ±317	25.5	19.7 ±13.7	27.8	12.3 ±14.0	2.8 ±2.8	10.9	3.1 ±7.3	25.6 ±16.8	31.2	30.2 ±31.3	12.3 ±8.0	39.4	5.5 ±6.5
<b>NOVA 2</b> ( $n = 461$ )	87 ±88	4.2	0.1 ±0.6	0.2	0.9 ±3.0	2.7 ±4.6	8.3	21.9 ±26.6	1.8 ±3.9	2.0	21.5 ±38.1	0.0 ±0.3	0.2	0.3 ±1.4
<b>NOVA 3<sup>#</sup></b> ( $n = 1496$ )	431 ±260	21.3	18.8 ±13.4	26.5	19.0 ±15.3	7.5 ±6.5	25.8	14.4 ±18.0	13.4 ±11.3	16.8	15.3 ±22.2	6.4 ±5.7	20.5	3.7 ±3.9
<b>NOVA 4<sup>#</sup></b> ( $n = 2569$ )	1020 ±472	49.0	32.1 ±16.9	45.5	13.1 ±16.0***	16.0 ±9.8	54.9	13.4 ±14.7	42.1 ±29.9	50.0	22.3 ±27.6***	10.9 ±5.4	39.9	2.6 ±10.9***

Data presented as mean ±SD; <sup>#</sup>tested for differences between mean protein, saturated fatty acids, sugar and fiber content of processed (NOVA 3) and ultra-processed (NOVA 4) foods with unpaired two-sided Welch t-tests; \*\*\* $p < 0.001$ ; E%, energy percent.

**Table 4: Contribution from meat and dairy alternatives to total intake (without supplements) of energy, qualitative aspects of the diet (protein, saturated fatty acids, sugar, fiber and micronutrients) in first-year students**

	Total (n = 142)	Vegans (n = 32)	Vegetarians (n = 66)	Omnivores (n = 44)	<i>p-value*</i>
Energy %	7.7 (2.7-11.3)	11.9 <sup>a</sup> (8.7-13.8)	6.6 <sup>b</sup> (1.6-10.2)	4.6 <sup>b</sup> (1.5-6.7)	<0.001
Protein %	11.7 (2.6-19.2)	18.1 <sup>a</sup> (7.4-26.1)	10.1 <sup>b</sup> (2.9-15.9)	6.7 <sup>b</sup> (0.8-10.5)	<0.001
SFA %	11.2 (1.3-15.4)	24.1 <sup>a</sup> (12.8-37.2)	7.3 <sup>b</sup> (0.8-9.4)	3.1 <sup>b</sup> (0.7-4.6)	<0.001
Total sugar %	3.4 (0.2-4.1)	4.5 <sup>a</sup> (1.1-5.5)	3.5 <sup>b</sup> (0.2-2.9)	1.7 <sup>b</sup> (0.1-1.9)	0.002
Fiber %	8.6 (3.0-11.5)	11.4 <sup>a</sup> (5.3-17.1)	8.1 <sup>ab</sup> (2.8-10.8)	6.1 <sup>b</sup> (1.9-7.8)	0.009
Vitamin B2 %	10.1 (1.8-14.3)	15.6 <sup>a</sup> (5.4-24.8)	9.3 <sup>b</sup> (1.7-11.5)	4.5 <sup>b</sup> (0.7-8.0)	<0.001
Vitamin B12 %	16.5 (0.0-16.9)	44.1 <sup>a</sup> (0.0-87.1)	8.6 <sup>b</sup> (0.0-8.6)	1.5 <sup>b</sup> (0.0-0.0)	<0.001
Folate %	8.8 (1.6-14.0)	13.4 <sup>a</sup> (4.6-20.0)	7.3 <sup>b</sup> (1.6-10.9)	6.1 <sup>b</sup> (1.0-12.4)	0.001
Iron %	10.8 (4.3-16.3)	13.8 <sup>a</sup> (5.9-21.6)	10.3 <sup>ab</sup> (3.6-14.9)	8.1 <sup>b</sup> (1.6-11.8)	0.025
Zink %	8.3 (2.3-13.2)	11.4 <sup>a</sup> (5.5-16.4)	8.1 <sup>ab</sup> (2.1-13.8)	4.5 <sup>b</sup> (0.8-7.7)	0.002
Calcium %	12.8 (2.8-19.8)	21.5 <sup>a</sup> (8.2-29.5)	10.1 <sup>b</sup> (2.3-15.4)	7.4 <sup>b</sup> (1.4-11.5)	<0.001

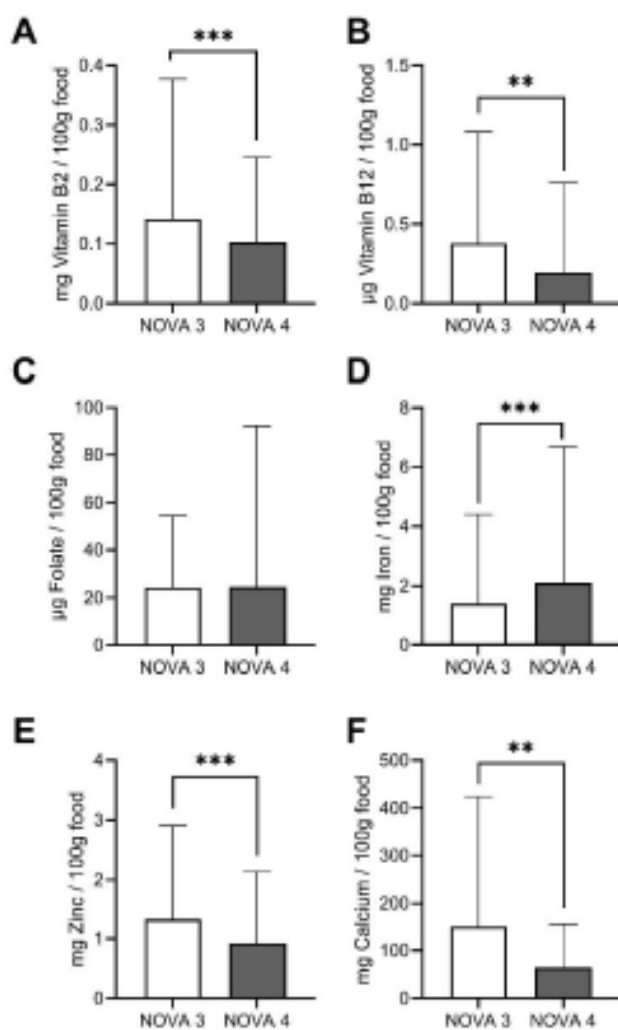
Data presented as median (interquartile range); \**p*-values refer to differences between diet groups using Kruskal-Wallis test with Bonferroni post-hoc test; <sup>a,b</sup> diet groups not sharing a common superscript letter are significantly different, *p* < 0.05; SFA, saturated fatty acids.

**Table 5:** Mean Vitamin B2, Vitamin B12, Folate, Iron, Zinc and Calcium content of consumed plant-based dairy alternatives ( $n = 484$ ) and milk/dairy products ( $n = 689$ ) as well as of consumed plant-based meat alternatives ( $n = 162$ ) and meat/meat products ( $n = 71$ )

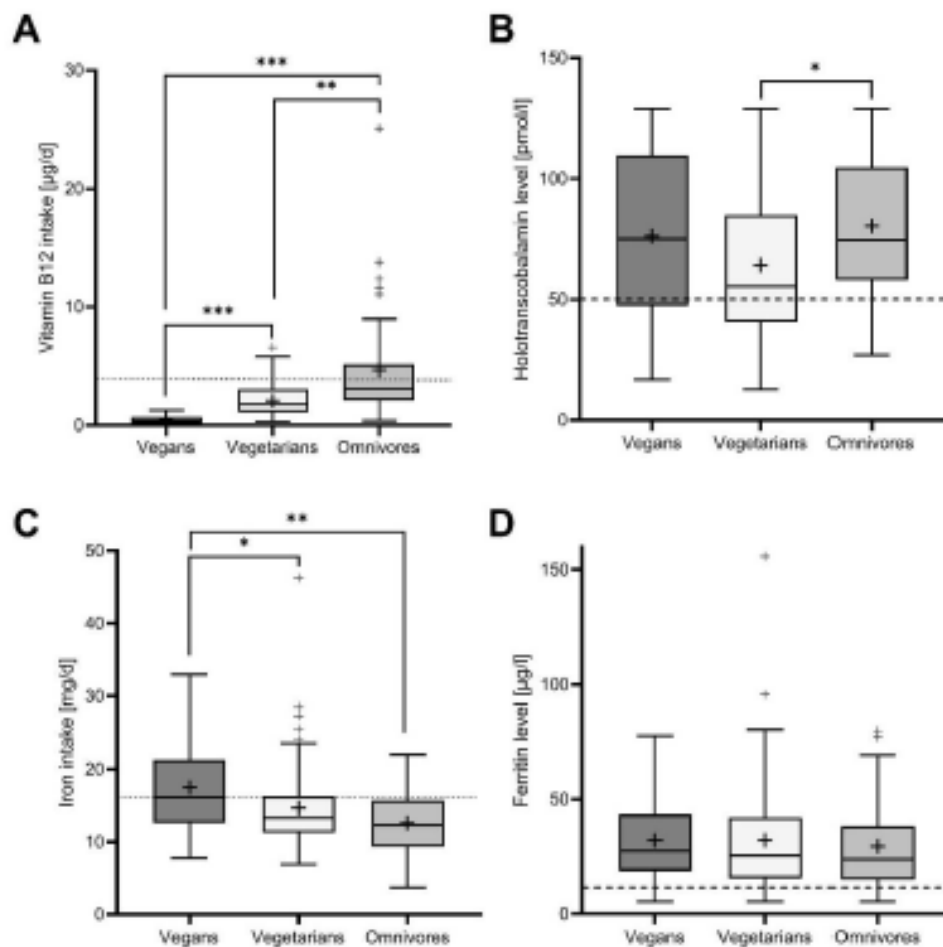
	B2 content (mg/ 100g)	B12 content ( $\mu$ g/ 100g)	Folate content ( $\mu$ g/ 100g)	Iron content (mg/ 100g)	Zinc content (mg/ 100g)	Calcium content (mg/ 100g)
Dairy Alternatives	0.06 $\pm$ 0.20	0.13 $\pm$ 0.40	11.84 $\pm$ 25.48	0.55 $\pm$ 0.45	0.25 $\pm$ 0.32	37.23 $\pm$ 49.80
Milk/Dairy products	0.22 $\pm$ 0.14***	0.86 $\pm$ 0.80***	14.73 $\pm$ 14.67*	0.18 $\pm$ 0.23***	1.54 $\pm$ 1.81***	306.58 $\pm$ 351.42***
Meat Alternatives	0.08 $\pm$ 0.08	0.01 $\pm$ 0.14	38.27 $\pm$ 56.45	2.20 $\pm$ 1.81	1.06 $\pm$ 0.90	99.80 $\pm$ 73.17
Meat /Meat products	0.17 $\pm$ 0.07***	1.30 $\pm$ 0.93***	6.32 $\pm$ 7.58***	1.33 $\pm$ 0.63***	2.01 $\pm$ 1.07***	15.34 $\pm$ 10.10***

All data are expressed as mean  $\pm$ SD; p-values from unpaired two-sided Welch t-tests (comparison between plant-based dairy alternatives and milk/dairy products; comparison between plant-based meat alternatives and meat/ meat products); \*  $p < 0.05$ , \*\*\* $p < 0.001$ .

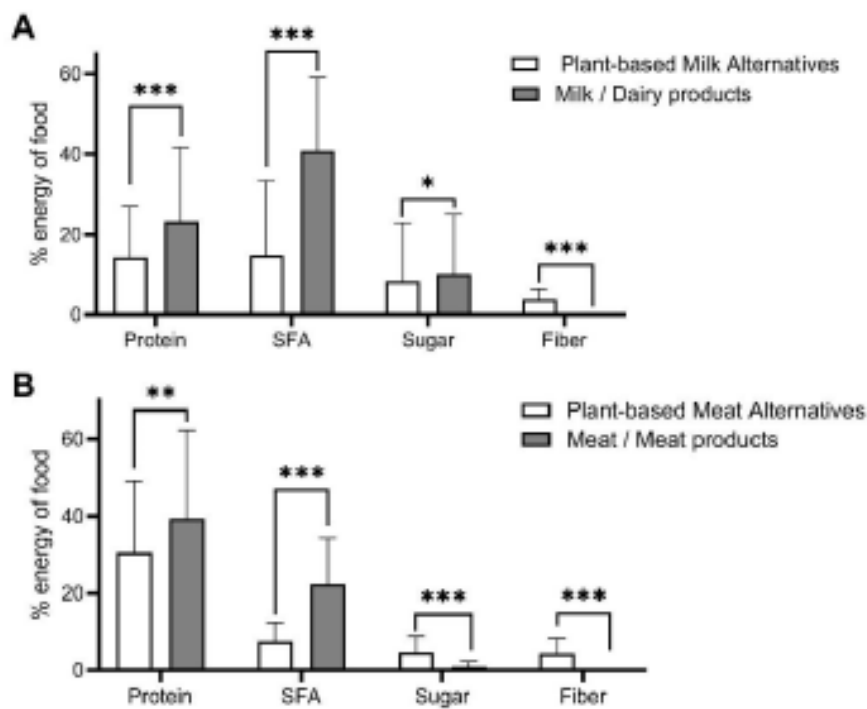
## Figures



**Figure 1:** Mean Vitamin B2 (A), Vitamin B12 (B), Folate (C), Iron (D), Zinc (E) and Calcium (F) content of consumed processed (NOVA 3,  $n = 1496$ ) and ultra-processed (NOVA 4,  $n = 2569$ ) foods from first-year students. All data are expressed as mean  $\pm$ SD; p-values from unpaired two-sided Welch t-tests; \*\* $p < 0.01$ , \*\*\* $p < 0.001$ .



**Figure 2:** Comparison of daily vitamin B12 intake (A) and Holotranscobalamin levels (B) as well as daily iron intake (C) and Ferritin levels (in females, D), all differentiated by diet groups; --- reference values: vitamin B12 intake (according to the German Society for Nutrition): 4  $\mu\text{g/d}$ , holotranscobalamin (according to laboratory specifications): 50 pmol/l, iron intake (according to the German Society for Nutrition): 16 mg/d (female), ferritin (according to laboratory specifications): 15  $\mu\text{g}$  (female); p-values from Kruskal-Wallis test with Bonferroni post-hoc test; \*p < 0.05, \*\*p < 0.01, \*\*\*p < 0.001.



**Figure 3:** Mean content of qualitative aspects of the diet (protein, saturated fatty acids, sugar and fiber) of consumed (A) plant-based dairy alternatives ( $n = 484$ ) and milk/dairy products ( $n = 689$ ) as well as of consumed (B) plant-based meat alternatives ( $n = 162$ ) and meat/ meat products ( $n = 71$ ) from first-year students ( $n = 142$ ). All data are expressed as mean  $\pm$ SD; p-values from unpaired two-sided Welch t-tests; \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ ; SFA, saturated fatty acids.

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Chapter V

**General Discussion**

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The present dissertation first examined conceptual differences between two food classification systems based on a market analysis (Chapter II). The two observational studies from Chapters III and IV provide current data on UPF consumption in Germany, investigate the impact of UPF consumption on diet quality and nutritional status, and contribute to the existing evidence regarding the association between UPF consumption and the risk of overweight. Based on these studies, the methods used to assess UPF consumption and the potential mechanisms underlying the health implications of UPF consumption are discussed, followed by resulting implications and outlook.

### *Methods to assess ultra-processed food consumption*

In all three studies presented in this dissertation, we used the NOVA classification system to determine the degree of food processing. NOVA is the most commonly utilized classification system in 95% of studies examining the relationship between UPF consumption and health outcomes published over the last years (Chen et al., 2020). The results from those studies consistently support the evidence for a link between UPF consumption and overweight and obesity (Pagliai et al., 2020). Although the NOVA classification system was chosen carefully, it is not without limitations. There are suggestions that NOVA is not robust enough to classify foods into discrete categories, as the criteria used are ambiguous and inconsistent (Gibney, 2019; Sadler et al., 2021). Specific processing techniques are, for example, attributed to NOVA 4 but can also be found in the other NOVA categories. The differentiation between home and industrial processing as a categorization criterion for NOVA is also a subject of critical debate (Gibney, 2019). This is because it is argued that undesirable contaminants such as acrylamide can be produced in both cases and that homemade foods may not be unequivocally different (Gibney, 2019). In addition, another source of uncertainty is the indication that UPFs contain many ingredients, which does not clearly distinguish the number of ingredients from which classification into the NOVA 4 category takes place or whether attention is paid to which ingredients are involved (Braesco et al., 2022).

Therefore, some critics argue that the unclear definition of UPF in the NOVA classification system makes it difficult to implement in data analysis, resulting in misclassification and coding differences among researchers (Braesco et al., 2022). Consequently, study results may become less comparable and affect the reliability of research findings (Gibney, 2019). In a study from France, over 150 food and nutrition specialists were asked to assign foods to the NOVA categories (Braesco et al., 2022).

Although assignments were consistent for some foods, overall consistency among the evaluators was low. Even when ingredient information was available, the assignment consistency values ranged only between 0.32 and 0.34 (values can range from 0 to 1, where 1 indicates full agreement; Braesco et al., 2022).

In addition, cultural differences can amplify coding differences. For example, in a cross-sectional study of 19,363 Canadian adults, UPFs comprised 45% of daily energy intake, with ultra-processed bread being the largest contributor to the NOVA 4 category (Nardocci et al., 2019). This contrasts with results from the NutriNet-Santé cohort (n = 74,470 participants) in France, where UPFs accounted for 36% of daily energy intake, with confectionery, cookies, and cakes being the most consumed UPFs (Julia et al., 2018). In the French study, bread was consistently assigned to processed foods (NOVA 3 category), as it was assumed that the bread mainly comes from artisan bakeries that only use a few ingredients and no additives (Julia et al., 2018). Those different classifications of bread are based on different dietary assumptions that had to be made because the tools used to collect food intake data were not specifically validated for estimating UPF consumption. This may have led to the misclassification of foods in the NOVA categories, which, in turn, may have led to the misinterpretation of the associations found between UPF consumption and health outcomes. Novel 24h-recalls and FFQs, designed to collect food intake data with information about food processing, allow for a more straightforward categorization into the NOVA categories and reduce uncertainty (Dinu et al., 2021; Neri et al., 2023). However, if a standard dietary assessment tool (FFQ or 24h-recall not designed to assess the level of processing) is employed, it is possible to achieve an acceptable level of validity and reliability in identifying UPFs through a few additional methods (Martinez-Steele et al., 2023).

First, the people who classify the food (coders) should be aware of the topic. Studies show that with adequate training, the agreement rate between coders can be improved when classifying food according to NOVA (Khandpur et al., 2021). In three large cohort studies from the US (the Nurses' Health Studies, the Health Professionals Follow-up Study, and the Growing Up Today Study), the categorization of foods from semi-quantitative FFQs showed that at first 70% of the foods could be assigned equally by three researchers. After discussing with dietitians and obtaining more product information, a coding agreement of 95.6% was achieved (Khandpur et al., 2021). Sneed et al. (2023) tested the reliability and validity of training for coders to assign NOVA categories to foods collected

via 24h-recall. They found that through training (based on literature and presentations on UPF), high interrater reliability with an overall agreement of 88.3% was achieved (Sneed et al., 2023).

A further extension of the NOVA classification system through machine learning may facilitate the automation of the classification process. A first approach was proposed by Menichetti et al. (2023). The FoodProX algorithm has been developed to replicate manual NOVA classification from nutritional information and provide an automated and reproducible continuous processing score (Menichetti et al., 2023). However, this algorithm relies only on the nutrients of the foods provided. Although nutrient data from the nutrition facts are correlated with the NOVA classification, ingredients and food label information, not nutrient composition alone, are the main drivers for determining the NOVA category (O'Connor et al., 2023b; Steele et al., 2023). Therefore, food composition databases would need to provide not only regularly updated nutrient contents but also a list of ingredients of brand-specific foods that need to be incorporated into novel algorithms to make them a useful tool for data analysis (Steele et al., 2023).

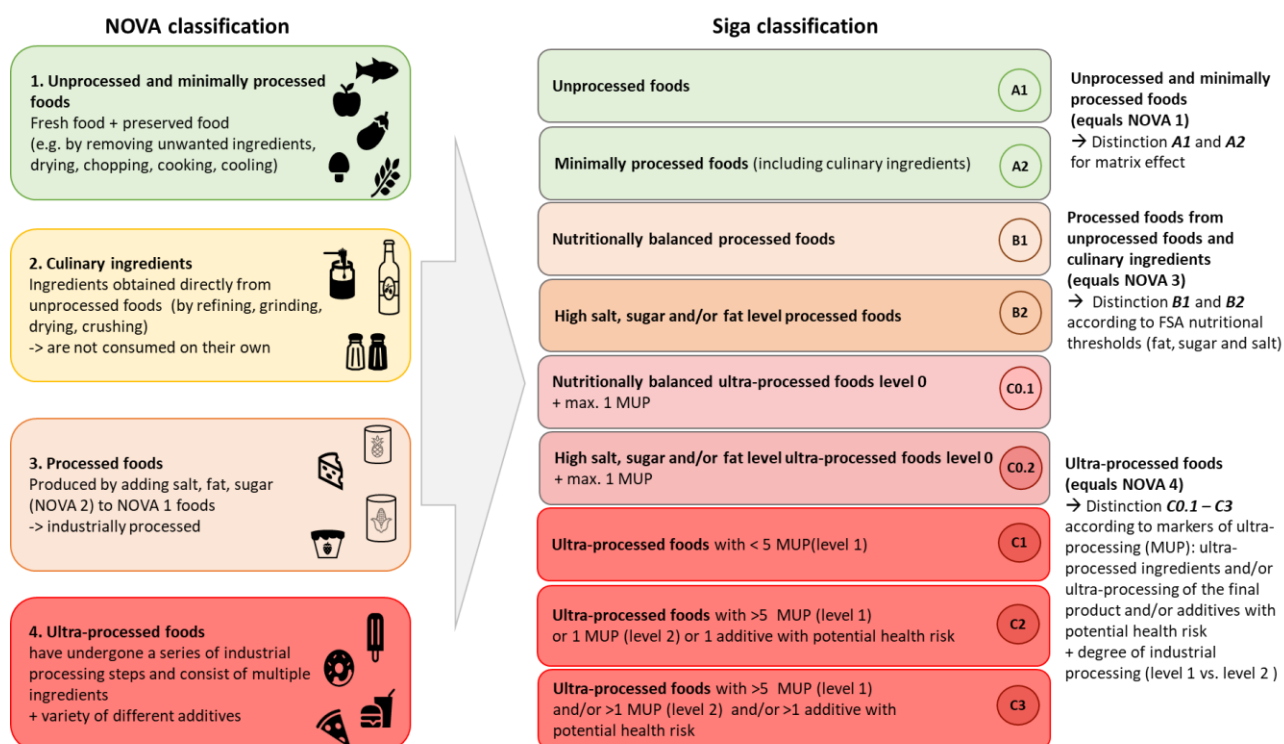
As recommended in the best-practice approach of Martinez-Steele et al. (2023), the categorization process should be made as transparent and comparable as possible. This is a three-step iterative approach. In the first step, a list of all consumed foods is compiled. Single-ingredient foods can easily be assigned to NOVA category 1 or 2, while for multi-ingredient foods, a decision must be made as to whether the food is homemade or industrially produced. Information such as brand name, preparation method (homemade, frozen, microwaveable), place of preparation (home, restaurant, vending machine), or certain other keywords such as fresh, frozen, unpackaged, or instant are included in the decision. If this information is provided, the food product can be assigned to either of the four NOVA categories (step 2). If there is uncertainty or disagreement between coders, the foods are flagged for sensitivity analysis (step 3) to determine the impact of these uncertainties on the distribution of the NOVA group estimates and their associations with health outcomes (Martinez-Steele et al., 2023).

The challenges of classifying foods according to the NOVA system, particularly depending on the data collection method, were evident in the three studies in Chapters II, III, and IV. In the market analysis presented in Chapter II, the focus was on packaged foods available in food retail. With access to information on manufacturers, nutritional content, and ingredients, we could accurately assign these foods to their respective NOVA categories. However, the observational studies presented in Chapters III and IV employed different dietary assessment tools, introducing variability in classification. In

Chapter III, the data were collected using standard methods, including 24h-recalls and FFQs. Due to limited information, foods were often assigned to a lower NOVA category, potentially underestimating UPF intake. This limitation was acknowledged in the study (Chapter III). To address this limitation, data collection in Chapter IV was based on a more detailed 3-day dietary record, which included crucial information such as fat content, quantity, preparation methods, and, importantly, the manufacturer or brand of the food consumed. All data evaluations were conducted by a trained, multidisciplinary team of nutritionists and dietitians to mitigate the potential for categorization bias. Despite these efforts, sensitivity analysis reported in Chapter IV revealed that the coders categorized 5.9% of the foods differently, leading to a range of 45.5% to 53.0% in energy intake from UPF. This variability is comparable to other studies, where foods marked for sensitivity analysis due to classification uncertainty ranged from 5% to 10% (Khandpur et al., 2021), with UPF consumption varying between 53.4% and 60.1% of total energy intake (Steele et al., 2023). Overall, transparently reporting the impact of uncertainties on NOVA category estimates will enhance the comparability of findings across studies.

Expanding the NOVA classification system is another approach that addresses its criticisms. The Siga classification, introduced by Davidou et al. (2020), extends the NOVA classification system by incorporating additional subgroups (**Figure 1**). While originally developed as a practical tool to help food manufacturers improve the quality of processed foods, the Siga classification may also contribute to the scientific debate on the NOVA classification and the definition of UPF.

Nine groups were derived from the existing four NOVA categories in the Siga classification system (Davidou et al., 2021). These consider (i) the impact of processing on the food matrix, (ii) an assessment of the salt, sugar, and fat content in comparison with the nutritional recommendations of the Food Standard Agency (FSA) and the World Health Organization (WHO), and (iii) so-called markers of ultra-processing (MUP). These MUP can be either ultra-processed ingredients (e.g., refined oils, glucose-fructose syrup) or the ultra-processing of the final product (e.g., by extrusion of cereals). Additives such as emulsifiers and flavorings are also MUP (Davidou et al., 2020, 2021).



**Figure 1:** Comparison of the NOVA classification system with the Siga classification system according to the degree and extent of food processing (modified according to Davidou et al., 2020).

The categorization of processed foods into the Siga groups C0.1 to C3 is based on the number of MUP and the level of processing. Two distinct processing stages are therefore distinguished. Level 1 of industrial processing, for instance, encompasses chemical synthesis, whereby the end product or ingredient retains a structural and compositional resemblance to its natural counterpart (e.g., protein isolates). In contrast, level 2 of industrial processing involves a more pronounced chemical synthesis, leading to significant structural or compositional changes in the food or ingredient matrix (e.g., protein hydrolysates). Additionally, processed foods are evaluated based on the potential health risks associated with additives, as outlined by the European Food Safety Authority (EFSA), the French Agency for Food, Environment and Occupational Health & Safety (ANSES), and recent scientific literature (Davidou et al., 2020). **Table 1** shows the most used MUP, characterized among over 22,000 UPFs, representative of products in French supermarkets (Davidou et al., 2020).

**Table 1:** Most used markers of ultra-processing (MUP) found in the study by Davidou et al., 2020

Ingredient / additive	Level of ultra-processing
Refined oils	MUP level 1
Aromatic extracts and natural flavors	MUP level 1
Hydrolyzed sugars	MUP level 2
Artificial/synthetic aroma	MUP level 2
Starches	MUP level 1
E322 (lecithin)	MUP level 1
Modified starches	MUP level 2
Isolated animal and vegetable proteins	MUP level 1

The Siga classification system may assist in reducing the risk of food misclassification, as it is the only classification system regarding the degree of food processing that incorporates a quantitative nutritional assessment, evaluating the nutritional content in relation to dietary recommendations (Sadler et al., 2021). Unlike the NOVA classification system, Siga allows for the separate assessment of the effects of processing and formulation on the health impact of processed foods, enabling the evaluation of specific risk factors, such as sugar content, in relation to health outcomes (Behnlian et al., 2023). However, studies that examine the association between food and health outcomes using the Siga classification are currently lacking. This gap may be due to the need for detailed dietary data on food processing and formulation, which is often not provided by existing dietary assessment tools. Obtaining this information from the manufacturers represents an additional challenge to data collection. This is, however, crucial for achieving more accurate results and strengthening the evidence base on the link between UPF consumption and health outcomes.

In conclusion, while the best practice approaches for applying NOVA or the possible extension or differentiation by Siga may enhance the efficiency, transparency, and accuracy of dietary data evaluation, the limitations of the current definition of UPFs remain. UPFs encompass a diverse group of foods ranging from nutritionally balanced frozen vegetable mixes and pre-packed wholegrain bread with one industrial processed ingredient like dextrose or invert syrup, to sugar-sweetened beverages and ready-to-heat-products with a variety of different processed ingredients and additives (Monteiro et al., 2019). It is unclear whether the consumption of all these foods is associated with adverse health effects. Food-group-specific analyses show that certain food groups, such as sugar-sweetened

beverages and processed meat, are the main drivers of the adverse health effects of UPF consumption, while inverse associations have been observed for other food groups, such as bread and yogurt/dairy desserts (Mendoza et al., 2024). However, the associations found are so far inconsistent (Dicken and Batterham, 2024), and when certain food groups were removed from the analysis, the adverse health effects of UPF consumption were reduced but remained significant (Mendoza et al., 2024). Therefore, much work remains to be done to better understand which characteristics of UPFs are the main drivers of the adverse health effects.

### *Potential mechanisms underlying the associations between ultra-processed food consumption and weight gain*

The two conducted observational studies showed that half of the daily energy intake of young adults can be attributed to UPF consumption (Chapters III & IV). Our results align with numerous cross-sectional as well as prospective cohort studies that have reported similar associations between UPF consumption and increased risk for overweight (Canella et al., 2014; Juul et al., 2018; Mendonça et al., 2016; Monteiro et al., 2018; Nardocci et al., 2019; Silva et al., 2018). Several meta-analyses even demonstrated a dose-response relationship, indicating that higher consumption of ultra-processed foods is linked to an increased risk of overweight (Askari et al., 2020; Lane et al., 2021; Moradi et al., 2021; Pagliai et al., 2020). However, causality between UPF consumption and weight gain can only be derived from intervention studies. The first highly controlled intervention study by Hall et al. (2019) investigated the impact of UPF consumption on energy intake and body weight change in a group of 20 inpatient adults (ten women and ten men, aged  $31.2 \pm 1.6$  years, BMI:  $27 \pm 1.5$  kg/m<sup>2</sup>). *Ad libitum* energy intake was 508 kcal/day higher with the UPF diet compared to a largely unprocessed diet adjusted for energy, macronutrient, and fiber content. During the 14 days of each intervention, the observed energy intake correlated with body weight changes. On the UPF diet, the participants exhibited a gain of 0.9 kg in body weight, while they lost 0.9 kg on the unprocessed diet (Hall et al., 2019). These findings suggest that there is indeed a causal relationship between high UPF consumption leading to excess energy intake and an increased risk for weight gain. Several mechanisms have been proposed to explain these findings, which will be discussed in the following.

High energy density is a characteristic of UPFs that is known to positively influence energy intake (Rolls, 2009). In Chapter IV, we were able to show that the energy density of UPF was more than 30%

higher than that of processed food ( $p < 0.001$ ). Moreover, in the KOPS cohort (Chapter III), the highest UPF consumers (tertile 3, >55% daily energy intake from UPF) exhibited a greater consumption of energy-dense foods when compared to the lowest UPF consumers (tertile 1, <38% daily energy intake from UPF). This finding aligns with the results of other cross-sectional studies that consistently demonstrate a positive association between UPF intake and dietary energy density (Cediel et al., 2021; Neri et al., 2022). The results of an intervention study conducted in 18 normal-weight women showed that increased energy density positively influenced *ad libitum* energy intake and led to overconsumption, regardless of macronutrient composition or palatability (Bell et al., 1998). Food consumption appeared to be more consistent with the weight of the food than with energy content (Bell et al., 1998). This effect has been confirmed by the intervention study from Hall et al. (2019), as the non-beverage energy density differed substantially between the ultra-processed and the unprocessed diet, mediating 45% of the increased energy intake on the ultra-processed diet (Fazzino et al., 2023). However, a recently published analysis suggests that insensitivity to calories is only occurring up to a level of  $\sim 1.75$  kcal/g food and that for higher energy-dense meals, people show sensitivity to calories, with a slight decrease in energy intake (e.g., by reducing portion size) (Flynn et al., 2022).

Another mechanism linking UPF consumption to the risk of overweight relates to the lower protein content of UPF. There is evidence that a higher protein intake increases satiety compared to diets of lower protein content (Halton and Hu, 2004). The findings of Chapter IV reveal that, although UPFs account for 46% of total protein intake, their protein content is significantly lower (13%) compared to processed foods (19%). Similar results were reported in the NHANES cohort, where the protein content of processed foods and UPFs was 25.3% and 9.5%, respectively (Steele et al., 2018). The same study further demonstrated that as the proportion of energy intake from UPFs increased, the proportion of energy intake from protein decreased, and total energy intake rose while absolute protein intake remained relatively constant (Steele et al., 2018). This pattern supports the *protein leverage hypothesis*, suggesting that diets with low protein content may lead to excess energy consumption as individuals attempt to achieve a specific protein intake target (Simpson and Raubenheimer, 2005).

In addition to a high energy density and a low protein content, UPFs also have a higher sugar content and a lower fiber content (Chapter IV). Poor carbohydrate quality with a low fiber intake may impair satiety (Fardet, 2016), presumably by a higher energy density, reduced food volume, and lower

chewability, leading to lower satiation as well as lower fermentation to short-chain fatty acids in the colon (Slavin, 2005). Furthermore, diets high in sugar may induce neuroadaptations in the reward system that decouple eating behavior from caloric needs and lead to excess energy intake (Freeman et al., 2018). In the context of UPFs, the concern extends beyond high sugar content to include highly processed carbohydrates with a high glycemic load, which are rapidly absorbed and may disrupt homeostatic appetitive responses (Kelly et al., 2022), further contributing to excess energy intake and thereby to weight gain.

Although poor diet quality is considered a possible factor for the associations between UPF consumption and being overweight, almost all of the previously mentioned epidemiological studies adjusted for energy intake and diet quality in data analysis. According to a recent review, 93% of all dietary adjustments (e.g., for nutrients, diet quality, or food groups) did not alter or explain the significant associations between UPF and obesity outcomes in prospective cohort studies (Dicken and Batterham, 2022). This is in line with the observation made in a large Italian population cohort (n = 22,895) that analyzed the association between mortality risk and nutritional quality (assessed by the Nutri-Score) or the degree of food processing (assessed by NOVA) (Bonaccio et al., 2022). The authors found that UPF consumption remained associated with mortality even after the poor nutritional quality of the diet was accounted for (Bonaccio et al., 2022). The nutritional content of a food product and its degree of processing are two distinct dimensions that may be correlated but may also differ in some cases. This is also reflected by the findings presented in Chapter II: While the majority of UPFs analyzed in the market exhibited a suboptimal nutritional profile and were classified with a Nutri-Score C, D, or E, 16.4% demonstrated a favorable nutritional profile (Nutri-Score A) (Chapter II). Therefore, factors beyond the nutritional quality covered by the Nutri-Score may influence the associations between UPF consumption and excess energy intake leading to overweight.

UPFs are frequently distinguished by a high level of palatability potentially resulting in excess energy intake. The so-called hyper-palatability of these products results from the industrial ultra-processing, leading to a unique and tasty combination of fat, sugar, and salt (Dicken et al., 2024). In 2019, the descriptive definition of hyper-palatable foods (e.g., fast foods, sweets) was replaced by a quantitative definition that groups certain palatable-inducing ingredients into three clusters (Fazzino et al., 2019). Most hyper-palatable foods contain either a certain ratio of fat and sodium (> 25% kcal from fat,  $\geq 0.30\%$  sodium by weight) or a certain ratio of fat and simple sugars (> 20% kcal from fat, > 20% kcal

from sugars) or a certain ratio of carbohydrates and sodium ( $> 40\%$  kcal from carbohydrates,  $\geq 0.20\%$  sodium by weight). This data-derived definition of hyperpalatable foods revealed that 62% of foods in the US food system can be classified as hyper-palatable. Among them were foods that were not previously conceptualized as hyper-palatable (e.g., vegetables cooked in creams or sauces). Furthermore, the authors suggest that the food processing method, not the food item itself, is crucial for hyper-palatability (Fazzino et al., 2019). A prospective analysis based on a single *ad libitum* buffet meal revealed that in a sample of 82 young adults without obesity, eating more hyper-palatable foods was associated with a higher energy intake (Fazzino et al., 2021). Those findings may be explained by the mechanism that hyper-palatable foods modulate feeding-related neural systems and food-seeking behavior by inducing reward, which may result in overeating (Leigh et al., 2018). A secondary analysis of the intervention study by Hall et al. (2019) comparing ultra-processed versus minimally processed diets demonstrated that despite the diets being matched for sugar, salt, and fat content, the individual meals exhibited disparate amounts of energy from hyper-palatable foods, which may have positively influenced energy intake (Fazzino et al., 2023).

The current definition of hyper-palatable foods does not yet incorporate additives, such as flavorings, colorings, and non-caloric sweeteners, which are also utilized in ultra-processing to enhance the palatability of food products (Monteiro et al., 2019). As a result, the proportion of hyper-palatable foods may be underestimated for certain food groups like high-protein UPFs that contain more sweeteners and flavorings compared to non-protein enriched UPFs (Koop et al., 2024). Added flavors may be potential contributors to the development of overweight (Neumann and Fasshauer, 2022). This is based on the assumption that added flavors promote hedonic eating (e.g., eating for pleasure) because of the increased rewarding characteristics of those foods that may override the homeostatic control of food intake, leading to overconsumption and weight gain in the long term (Neumann and Fasshauer, 2022). However, there are currently no studies that analyzed the potential contribution of added flavors to excessive calorie intake and body weight gain in humans.

Lastly, industrial food processing or formulation can alter the food texture, which may result in products becoming softer and, therefore, faster to consume than foods that are harder or more chewy (Forde and Bolhuis, 2022). Foods with textures that require less structural breakdown during chewing require less lubrication and take less time to form a swallowable bolus, which may result in a higher eating rate (Forde and Bolhuis, 2022). A higher eating rate (g of food per minute) can then promote higher energy intake rates (kcal consumed per minute) and increase energy intake (Teo et

al., 2022). An analysis of 5 pooled studies, including a total sample of 327 foods, showed that energy intake rates differed between NOVA categories (Forde et al., 2020). Unprocessed foods showed a mean energy intake rate of  $35.5 \pm 4.4$  kcal/min, while UPFs had an energy intake rate of  $69.4 \pm 3.1$  kcal/min ( $p < 0.05$ ) (Forde et al., 2020). Similarly, in the intervention study conducted by Hall et al. (2019), ultra-processed meals were consumed more quickly than unprocessed meals, leading to a higher energy intake rate (Hall et al., 2019). To further investigate the impact of food texture, another crossover intervention study was conducted in which 50 participants were served four *ad libitum* lunch meals categorized as "soft minimally processed", "hard minimally processed", "soft ultra-processed", and "hard ultra-processed" with meals matched for total energy content (Teo et al., 2022). The results showed a significant effect of food texture on eating rate: hard foods were consumed more slowly, resulting in a 26% reduction in energy intake, while the intake was higher for both "soft minimally processed" and "soft ultra-processed" meals ( $p < 0.001$ ). The highest energy intake was observed with the "soft ultra-processed" meal, leading to an additional  $\sim 300$  kcal consumed compared to the "hard minimally processed" meal (Teo et al., 2022).

The texture of food can be influenced by both food processing and formulation (Gibney, 2022). Both of these factors are integrated into the UPF definition of Monteiro et al. (Monteiro et al., 2019; O'Connor et al., 2024). Nevertheless, some researchers contend that formulation and processing are two distinct aspects of food production (O'Connor et al., 2024), and it remains unclear whether the observed associations between UPF consumption and adverse health outcomes are driven by food processing, formulation, or a combination of both. Therefore, further research is needed to investigate the beneficial and harmful effects of food processing and formulation separately (Trumbo et al., 2024).

### *Potential mechanisms underlying the associations between ultra-processed food consumption and non-communicable diseases*

A new systematic review and meta-analysis of 25 prospective cohort studies demonstrates that UPF consumption is consistently associated with a higher risk of obesity, diabetes, hypertension, and dyslipidemia (Vitale et al., 2024). Preliminary research has also indicated an increased risk of gastrointestinal disorders such as irritable bowel syndrome, and mental health conditions such as depression, with the highest consumption of UPFs (Adjibade et al., 2019; Schnabel et al., 2018). A

prospective study of 19,899 adults also showed that participants with the highest UPF consumption (> 4 servings of UPFs per day) had a 62% relatively increased risk of all-cause mortality compared to subjects with low UPF consumption (< 2 servings per day) (Rico-Campà et al., 2019). The study also demonstrated a dose-response relationship, indicating that each daily serving of UPFs was associated with an 18% relatively increased risk of all-cause mortality (Rico-Campà et al., 2019). Although the associations between UPF consumption and the risk of NCDs are highly consistent, due to the study design, residual confounding cannot be ruled out in observational studies, and drawbacks from using heterogeneous dietary assessment tools (as discussed above) should be considered.

It is well established that being overweight is a significant risk factor for NCDs, including hypertension, coronary heart disease, type 2 diabetes, and certain types of cancer (GBD 2015 Obesity Collaborators, 2017). Nevertheless, the associations between UPF consumption and the risk of developing NCDs cannot be completely attributed to weight gain. A study from France comprising over 100,000 adults has demonstrated the relationship between the consumption of UPFs and the prevalence of type 2 diabetes (Srour et al., 2020). After a follow-up of 6 years, a positive association was observed between the consumption of UPFs and the risk of type 2 diabetes (HR: 1,15 [95% CI: 1,06; 1,25]), which remained significant even after adjustment for weight gain (HR: 1,13 [95% CI: 1,01; 1,27]) (Srour et al., 2020). In a substantial number of studies, the results were also adjusted for total energy intake, and the relationship between UPF consumption and NCDs remained significant (Fiolet et al., 2018; Srour et al., 2020). Consequently, in addition to the potential mechanisms promoting excess energy intake and weight gain that have been previously discussed, there might be other mechanisms that explain the associations between UPF consumption and the risk of NCDs.

An increase in UPF consumption is shown to be accompanied by increased food additive intake (Dunford et al., 2023). Non-nutritive artificial sweeteners, including sucralose, saccharin, and aspartame, are widely utilized in UPFs, particularly in high-protein UPFs (Koop et al., 2024). These sweeteners have the potential to influence glucose tolerance due to alterations in the gut microbiome (Suez et al., 2014). Emulsifiers (i.e., lecithin, mono- and diglycerides of fatty acids, carrageenan, and celluloses) may also contribute to dysbiosis with proinflammatory potential, thereby facilitating the development of obesity and other NCDs (Jiang et al., 2018). For instance, *in-vitro* and *in-vivo* studies have demonstrated that the emulsifier carrageenan, which is utilized in numerous UPFs, induces inflammation in the gut, which could impair glucose tolerance and increase insulin resistance (Bhattacharyya et al., 2019, 2012).

On the one hand, the low fiber content of UPFs may lead to an altered composition of the gut microbiome, as fewer fermentable carbohydrates reach deeper sections of the gut (Zinöcker and Lindseth, 2018). This may result in a decline in the diversity of the gut microbiome, a reduction in the production of short-chain fatty acids, and an impairment in the integrity of the intestinal barrier (Juul et al., 2021). Short-chain fatty acids have been linked to several beneficial properties, including anti-inflammatory, anti-carcinogenic, and anti-diabetic effects (Miclote and Van de Wiele, 2020). Furthermore, a reduction in the production of fermentation products may result in a diminished secretion of appetite-suppressing hormones, including GLP-1 (glucagon-like peptide-1) and PYY (peptide YY) (Dagbasi et al., 2020).

In addition, ultra-processed foods are often characterized by poor carbohydrate and fat quality with a high glycemic index and a high content of saturated fatty acids and trans fats (Fardet, 2018). Trans fatty acids can result from partial fat hardening during food processing and are associated with increased low-density lipoprotein (LDL) cholesterol levels (Verneque et al., 2020). However, there are established threshold values for the content of trans fatty acids in food products in Germany, and the Federal Institute for Risk Assessment (BfR) classifies the intake of trans fatty acids in Germany as low (Bundesinstitut Für Risikobewertung, 2013). In many UPFs, palm oil or palm kernel oil is used due to its natural flavor, its capacity to confer texture, and its thermal and oxidative stability, which are superior to those of other fat sources (Mba et al., 2015; Steele et al., 2021). The high saturated fat content of palm oil and palm kernel oil may explain the correlation between increased consumption of UPF and elevated levels of saturated fat intake. A diet high in saturated fats may also contribute to elevated levels of LDL cholesterol, a well-established risk factor for cardiovascular disease (Steele et al., 2021). Other ingredients in UPFs with potential adverse effects include carcinogenic substances such as acrylamide. This unwanted by-product can be formed primarily from the high-temperature cooking of foods containing reducing sugars and asparagine, such as French fries, crisps, and biscuits (EFSA 2015). Other contaminants resulting from processing, such as glycidyl fatty acid esters, which are predominantly found in refined vegetable fats, including palm fat, are also considered detrimental to human health due to the genotoxic-carcinogenic effect of glycidol (Bundesinstitut Für Risikobewertung, 2020). Another hypothesis suggests that contaminants migrate from contact packaging to foods. The extended shelf life of UPFs provides an opportunity for contamination with substances such as bisphenol A or phthalates from plastic packaging (Buckley et al., 2019). Such

substances have been linked to obesity, cardiovascular disease, and type 2 diabetes due to their endocrine-disrupting properties (Bergman et al., 2013).

### *Implications and outlook*

A variety of potential underlying mechanisms have been proposed, extending beyond the poor nutritional quality and high energy density of UPF, such as changes in texture, palatability, contaminants from processing or packaging, or the use of additives and other industrial ingredients (Fazzino et al., 2023; Srour et al., 2022). However, the relative contribution of individual mechanisms, as well as potential interactions or so-called *cocktail effects*, which refer to the cumulative negative impact of additives or processing-related contaminants on the human body (Touvier et al., 2023), have yet to be elucidated in more detail.

Further prospective long-term studies on the impact of UPF consumption on the risk of overweight and obesity, as well as other NCDs, are required that adhere to the best practice approach outlined by Martinez-Steele et al. (2023), including the recording of the manufacturers and brands of the products consumed in order to determine the consumption of UPFs transparently and comparably (Martinez-Steele et al., 2023). This standardized approach will facilitate the identification of key processing and formulation aspects of UPFs that may be responsible for the observed associations between UPF consumption and the risk of overweight and NCDs. In addition, it will allow for a more comprehensive assessment beyond the evaluation of nutritional quality alone. This assessment, however, relies on the validity of self-reported dietary data. Therefore, the use of objective biomarkers of UPF consumption has been suggested to improve comparability and reduce potential errors (Freedman et al., 2014; O'Connor et al., 2024). Using "omics" technologies, such as metabolomics, can help to identify biomarkers linked to UPF consumption as dietary intake induces metabolic changes that can be detected (Ryan et al., 2013). In a secondary analysis of the previously mentioned intervention study by Hall et al. (2019), specific metabolites that were identified as being associated with the consumption of artificial sweeteners and other additives were found following the ultra-processed diet (O'Connor et al., 2023a). However, the lack of available data represents a significant limitation, particularly given the diverse range of UPFs and their complex compositions with many different ingredients and additives. This variability makes comparison and the use of quantifiable parameters in observational studies challenging because the metabolites found due to

UPF consumption can only offer a partial representation, potentially leading to an underestimation of actual UPF intake.

Conducting intervention studies with adequate endpoints, such as the microbiome and markers of gut barrier integrity and immune function, is necessary to validate results from observational studies and, at the same time, to determine the underlying mechanisms of adverse health effects caused by UPF consumption. However, it should be noted that the holistic view of food as something that is more than the sum of its individual nutrients (Fardet, 2024) adds complexity to the analysis of mechanisms. This complexity cannot be adequately addressed by conventional reductionist approaches. It is, therefore, essential to control for diverse characteristics of UPF (e.g., energy density, texture, flavor) in intervention studies.

Previous intervention studies have primarily investigated the short-term effects of UPF consumption (Hall et al., 2019; Teo et al., 2022), and it remains unclear whether the observed effects persist over a more extended period of time (> four weeks), particularly in terms of their contribution to a sustained positive energy balance and weight gain (O'Connor et al., 2023b). In the intervention study conducted by Hall et al. (2019), food intake on the ultra-processed diet was found to significantly decrease over the two-week intervention period. This observation has prompted discussions regarding the potential transient nature of these effects and their relevance for long-term body weight regulation (Ludwig et al., 2019). In long-term intervention studies, however, the risk of drop-outs and lower compliance increases (Crichton et al., 2012), which makes implementation more difficult. One potential approach could be to combine the assessment of actual energy intake under controlled laboratory conditions (short-term intervention studies) with the evaluation of free-living energy intake in natural setting studies (Gibbons et al., 2014). Such free-living studies allow for measurements of eating behavior over an extended period and under more realistic conditions (Gibbons et al., 2014). However, it is essential to recognize that such studies may not be as precise or accurate in measuring food intake due to their less controllable nature, potentially also making extrapolation difficult (Hall, 2019).

Once the mechanisms involved have been further investigated and their contribution to energy intake and health effects have been quantified, a risk-associated definition of UPFs with less scope for subjectivity and uncertainty could be derived. Such a definition of UPF could guide food manufacturers and policymakers and provide a foundation for nutritional recommendations.

Given that UPFs constitute a significant portion of our food system (Hall, 2023), addressing their impact on public health is crucial. Next to the discussed physiological mechanisms, behavioral and environmental factors that shape food choices (Valicente et al., 2023) are important factors through which UPFs may contribute to excess energy intake and weight gain. UPFs are ubiquitously accessible (Luiten et al., 2016) and benefit from extensive marketing efforts. For instance, an analysis of food advertisements from the five largest supermarket chains in Belgium over one year revealed that more than 50% of the promoted products were ultra-processed (Vandevijvere and Van Dam, 2021). Especially people living in city areas with a low SES are more exposed to UPF advertisements than those in high SES areas (Fagerberg et al., 2019). This could partially explain why households with lower SES are particularly inclined to purchase larger quantities of UPFs (Coyle et al., 2022). On top of that, UPFs are frequently offered in large portion sizes (Young and Nestle, 2021), are often inexpensive (Gupta et al., 2019), and have a long shelf life (Weaver et al., 2014), making them more attractive than minimally processed alternatives and provide a form of food security. Therefore, it is crucial to not only understand how UPFs are linked to health but also to specifically address at-risk populations with tailored public health approaches. These approaches, especially when focused on supporting sociodemographic groups with the highest UPF intake, have the potential to reduce consumption without advocating for complete avoidance (Dicken et al., 2023).

A further aspect that has yet to be adequately addressed in assessing the health implications of UPFs is their impact on the environment. A lifecycle assessment across the entire UPF supply chain reveals that these products are linked to a range of negative environmental pressures (Fardet and Rock, 2020). UPF production is thereby characterized by extensive monoculture crops, high energy demands for processing, a long transport chain and excessive packaging (Anastasiou et al., 2022). In addition, the rise of UPF is impairing agrobiodiversity (Leite et al., 2022). Of the 7,000 plant species that could be used as human food, fewer than 200 are cultivated on a commercial scale, and just nine crops accounted for two-thirds by weight of all crop production (Pilling and Bélanger, 2019). UPFs are mostly produced with cheap and standardized ingredients from these few high-yielding plant species, such as corn, wheat, soy, and oilseeds (Fardet and Rock, 2020). The increasing homogeneity of the global food supply is also a potential threat to food security (Khoury et al., 2014).

In addition, UPF consumption contributes more to greenhouse gas emissions than minimally processed food consumption (Vellinga et al., 2023). However, the negative environmental impact of UPFs is not solely attributable to the numerous industrial processing stages, increased packaging, and

extended transportation (Fardet and Rock, 2020). Another significant contributing factor is the excess energy intake associated with high UPF consumption. In a representative sample of 2,121 French adults, higher energy intake partially explained the increased environmental pressures observed among participants with high UPF consumption (Kesse-Guyot et al., 2023). Additionally, a longitudinal study from Spain, including 5,879 participants, found that those who reduced their UPF consumption from baseline to the two-year follow-up also decreased their environmental impact regarding greenhouse gas emission and energy use, whereas water use increased as the proportion of UPF in the diet was reduced (García et al., 2023).

In the context of a sustainable food system transformation leading to healthier and more sustainable diets (Willett et al., 2019), the impact of food processing and formulation is important not only in light of the previously discussed links between UPF and human health but also because of the increasing recognition of the environmental impacts associated with UPF consumption.

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## Summary

A substantial body of research links the consumption of ultra-processed food (UPF) with an increased prevalence of non-communicable diseases. However, the definition of UPF is controversially discussed. The health assessment of a product is currently conducted based on the voluntary use of the nutrition label Nutri-Score to inform consumers about the overall nutritional quality of the food. The aim of the first study was to assess the labelling frequency of the Nutri-Score in German food retailing based on a market analysis and afterwards to compare the Nutri-Score with the degree of food processing using the NOVA classification. At the time of data collection, a total of 2,333 products were examined, of which only 12% were labelled with the Nutri-Score. The majority of these products were labelled with the favorable Nutri-Scores A and B. All products labelled with Nutri-Score C, D and E were classified as ultra-processed (NOVA 4), but also 41% of products labeled with Nutri-Score A.

Since data on the trends of UPF consumption in Germany, are scarce, we analyzed in a second study the prevalence of UPF consumption in childhood/adolescence and adulthood of 182 participants in the Kiel Obesity Prevention Study (KOPS). During childhood/adolescence ( $13.1 \pm 1.9$  years) a low UPF-based dietary pattern was observed, while in adulthood ( $26.7 \pm 2.2$  years), UPFs accounted for almost half of the daily energy intake (46%). In young adults, a high consumption of UPF was associated with both prevalence and incidence of overweight. In addition, high UPF consumption was associated with markers of poor diet quality, like a lower intake of fiber and a higher intake of salt and energy-dense foods.

To gain further insights into the qualitative aspects of UPF, a third study was conducted to examine the nutrient density of UPF consumed by first-semester students. The consumption of UPF was evaluated in 142 subjects with vegetarian, vegan and omnivorous diets using 3-day dietary records. To ascertain the nutritional quality of the consumed foods, the mean nutrient content (based on nutritional databases) was compared between processed foods (NOVA 3,  $n = 1,496$ ) and UPFs (NOVA 4,  $n = 2,569$ ). UPFs constituted 49% of the daily energy intake, irrespective of the eating pattern and contributed to a significant portion of nutrient intake across all diet groups. UPFs exhibited significantly lower contents of protein, fiber, vitamin B2, vitamin B12, folate, zinc and calcium in comparison to processed foods (NOVA 3). The prevalence of low micronutrient intake was high across all diet groups, with a particularly high prevalence observed among vegans and

vegetarians. This can be attributed to the comparatively low micronutrient content of UPFs and ultra-processed plant-based alternatives, when compared to animal products.

In conclusion, the findings of the three studies indicate that especially a high energy density and low nutritional quality of UPFs could explain the observed associations with overweight and other non-communicable diseases. However, it has already been demonstrated that the correlation between a high intake of UPF and adverse health outcomes persisted even after the nutritional quality of UPF (by using the Nutri-Score) was accounted for. Accordingly, future studies should provide greater detail regarding other characteristics of UPF, such as texture, palatability, or the use of additives, to elucidate the underlying factors contributing to the observed associations.

## Zusammenfassung

Der Verzehr hochverarbeiteter Lebensmittel (engl.: *ultra-processed food*, UPF) ist heute in vielen Studien mit einer erhöhten Prävalenz von nicht-übertragbaren Erkrankungen assoziiert. Die Definition von UPF wird jedoch wissenschaftlich kontrovers diskutiert. Eine gesundheitliche Bewertung von Lebensmitteln erfolgt derzeit durch die freiwillige Nährwertkennzeichnung mithilfe des Nutri-Scores. Ziel der ersten Studie war es, anhand einer Marktanalyse die Häufigkeit der Verwendung des Nutri-Scores im deutschen Lebensmitteleinzelhandel zu untersuchen und anschließend den Nutri-Score mit dem Grad der Verarbeitung der Lebensmittel anhand der NOVA Klassifikation zu vergleichen. Von 2.333 untersuchten Produkten waren zum Zeitpunkt der Datenerhebung lediglich 12% mit dem Nutri-Score gekennzeichnet. Diese wiesen überwiegend die günstigen Nutri-Scores A und B auf. Als hochverarbeitet (NOVA 4) wurden alle mit Nutri-Score C, D und E gelabelten Produkte klassifiziert, aber auch 41% der mit Nutri-Score A gekennzeichneten Produkte.

Da Zahlen aus Deutschland über die Entwicklung des Verzehrs von UPF fehlen, wurde in einer zweiten Studie bei 182 ProbandInnen der Kieler Adipositas Präventionsstudie (KOPS) die Prävalenz des UPF-Konsums in der Kindheit und im Erwachsenenalter untersucht. Während sich in der Kindheit (13.1 ± 1.9 Jahre) ein Ernährungsmuster mit niedrigem Konsum von UPF zeigte, machten im Erwachsenenalter (26.7 ± 2.2 Jahre) UPF fast die Hälfte der täglichen Energieaufnahme (46%) aus. Ein hoher Konsum von UPF war sowohl mit der Prävalenz als auch mit der Inzidenz von Übergewicht assoziiert. Zudem zeigte sich eine Assoziation zwischen einem hohen Verzehr von UPF und einer geringeren Aufnahme von Ballaststoffen und einer höheren Zufuhr von Salz und energiedichten Lebensmitteln.

Um weitere qualitative Aspekte von UPF zu untersuchen, wurde in einer dritten Studie die Nährstoffdichte von UPF bei Erstsemesterstudierenden genauer untersucht. Bei 142 ProbandInnen mit vegetarischer, veganer und omnivorer Ernährungsweise wurde der Verzehr von UPF mithilfe eines 3-Tage-Ernährungsprotokolls erfasst. Zur Beurteilung der Nährwertqualität der Lebensmittel wurden die mittleren Nährstoffgehalte (basierend auf Nährwertdatenbanken) zwischen verarbeiteten Lebensmitteln (NOVA 3, n = 1.496) und UPF (NOVA 4, n = 2.569) verglichen. Unabhängig von der Ernährungsweise machten UPF 49% der täglichen Energieaufnahme aus und trugen damit wesentlich zur Nährstoffzufuhr bei. Im Vergleich zu verarbeiteten Lebensmitteln enthielten die verzehrten UPF jedoch signifikant weniger Protein, Ballaststoffe, Vitamin B2, Vitamin B12, Folsäure, Zink und Kalzium.

Die Prävalenz einer geringen Mikronährstoffaufnahme war bei allen Ernährungsweisen und insbesondere bei veganer und vegetarischer Ernährungsweise hoch. Dies könnte durch einen geringen Gehalt an Mikronährstoffen in UPF und in hochverarbeiteten pflanzlichen Alternativen im Vergleich zu tierischen Produkten erklärt sein.

Insgesamt deuten die Ergebnisse der drei Studien darauf hin, dass vor allem eine hohe Energiedichte und geringe Nährwertqualität von UPF die Assoziationen mit Übergewicht und anderen nichtübertragbaren Krankheiten erklären könnte. Allerdings wurde bereits gezeigt, dass der Zusammenhang zwischen einem hohen Konsum von UPF und negativen gesundheitlichen Auswirkungen auch dann bestehen blieb, wenn für das Nährwertprofil mithilfe des Nutri-Scores korrigiert wurde. Daher sollte zukünftig untersucht werden, welche weiteren Charakteristika von UPF, wie beispielsweise die Textur, die Schmackhaftigkeit oder die Verwendung von Zusatzstoffen in diesem Zusammenhang bedeutsam sind.

