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Journal Article

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Publication date:
2024-12

Permanent link:
https://doi.org/https://doi.org/10.3929/ethz-b-000701817

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Originally published in:
Food Research International 197, https://doi.org/10.1016/j.foodres.2024.115213

Funding acknowledgement:
- Gab resolutIon in sAfety, NuTritional, alLergenicity and Environmental assessments to promote Alternative ()

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Food Research International 197 (2024) 115213



Contents lists available at ScienceDirect

Food Research International

journal homepage: www.elsevier.com/locate/foodres





Comparing the nutritional value and prices of meat and milk substitutes with their animal-based benchmarks across six European countries

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ARTICLE INFO

Keywords:
Meat and dairy substitutes
Alternative proteins
Market research
Product prices
Nutrition

ABSTRACT

Since overconsumption of animal-sourced foods is directly linked to multiple environmental and health issues, a dietary shift is imperative. One approach to facilitate this change is the production of substitutes for animal-sourced foods based on plant-based or novel ingredients. However, to be a valid alternative, substitute products must match animal-sourced foods regarding their nutritional value while being price competitive. To understand where substitutes currently stand in that regard, this study presents a novel dataset containing the prices, main ingredients, and nutritional composition of almost 2600 substitute products as well as prices of approximately 7500 conventional products sold in major supermarket chains in France, Germany, Italy, the Netherlands, Spain, and the United Kingdom.

Although comparative analyses (non-parametric two-sided Wilcoxon rank-sum tests at a 5 % significance level) of the results indicate that the meat substitutes generally contain a higher level of dietary fiber with lower saturated fats, these meat substitutes often also have lower protein quality and higher salt and sugar levels than the conventional products. On average, meat substitutes were found to be 24 to 115 % more expensive compared to conventional meat, except for the German samples where price parity has been reached. Among milk substitutes, only soy-based products have favorable macronutrient profiles. The average price premium charged for milk substitutes compared to cows' milk is 35 to 58 %. In general, fortification rates of substitutes should be increased to ensure sufficient supplies of micronutrients, particularly among meat substitutes where fortification rates are below 20% except for the Netherlands. Following these results, certain individual products already provide high nutritional value at low costs. However, further improvements are required for substitutes to become a compelling alternative at scale.

1. Introduction

Food systems worldwide are among the major contributors to multiple environmental challenges that include climate change, biodiversity loss, land use change, and freshwater depletion (Daskalova et al., 2020; Foley et al., 2005; Molden, 2007; Willett et al., 2019). In high-income regions, contemporary diets have been associated with several health issues and non-communicable diseases (Hu, 2011; Tilman & Clark, 2014; Willett et al., 2019). Since both issues are closely linked to a significant overconsumption of animal-sourced foods, a transition towards more plant-based diets is imperative (Green et al., 2022; Willett et al., 2019). However, changing meat consumption patterns is particularly difficult (McBey et al., 2019).

One approach to facilitate this change, which has been gaining momentum in recent years, is the production of substitutes based on plant-based or novel protein-rich ingredients. These products aim to mimic sensorial and functional properties of animal-sourced foods while causing lower environmental impacts in their production (Nezlek & Forestell, 2022). In principle, they aim to allow consumers to move away from animal-sourced foods without significantly altering their dietary habits or impairing their eating experience (He et al., 2020). However, to be a relevant facilitator in the global food system transformation, substitute products will need to be adopted on a large scale. Further, they must fulfill their designated role of replacing animal-sourced foods in people's diets to effectively reduce the pressure of food systems on the environment. If, instead, substitute products merely replaced other dietary components like unprocessed grains or pulses, the additional processing steps in the manufacturing process of substitutes could

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https://doi.org/10.1016/j.foodres.2024.115213
Received 19 June 2024; Received in revised form 26 August 2024; Accepted 17 October 2024
Available online 23 October 2024
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possibly increase environmental impacts. For example, processing was found to be responsible for significant environmental impacts from several meat substitutes based on soy, wheat, dairy, and mycoprotein (Smetana et al., 2015). However, the number of sustainability assessment studies on meat substitutes is relatively limited and the studies often lack transparency (Shanmugam et al., 2023).

Taste, familiarity, and convenience have been shown to be among the key factors for a high acceptance of substitutes for animal-sourced foods among consumers (Elzerman, Hoek, van Boekel, & Luning, 2011; Michel, Hartmann, & Siegrist, 2021) and are likely factors to determine their uptake in the population. However, it is important that consumers are able to maintain or even improve the nutritional value of their diets by the substitution of animal-sourced foods. Despite the above-mentioned health issues associated with animal-sourced foods, meat and dairy products are an important source of essential nutrients such as amino acids, minerals, and vitamins in contemporary diets (Beal et al., 2023). To be a sustainable alternative on a large scale, substitute products must therefore match or even outperform animal-sourced foods in terms of their nutritional value. Furthermore, substitute products should be available at an affordable price to ensure accessibility among consumer groups with lower incomes and to increase competitiveness with conventional animal-based products. Considering the challenges that affordability and nutrition pose to substitutes as a replacement for animal-sourced foods, it is important to understand where currently available substitute products stand in comparison with animal-based benchmarks and how they will need to be improved in the future.

To that end, this study presents a novel dataset containing the prices, main ingredients, and nutritional composition of almost 2600 substitute products as well as prices of approximately 7500 conventional milk and meat products sold in major supermarket chains in France, Germany, Italy, the Netherlands, Spain, and the United Kingdom (see supplementary information (SI) 2&4). These six countries were selected because they cover between 70 – 80 % of the total European market for substitutes (GFI Europe, 2023). Further, supermarkets are the most frequented retailer type among consumers to buy substitute products (Smart Protein, 2023). Consequently, the data presented here is representative of the product variety an average European consumer encounters these days.

The representativeness of the current market situation, the large variety of substitute product categories including cream, dessert, egg, fat, meat, milk, seafood, spread, and yogurt, and the wide geographic scope make this data set a useful resource for dietary or economic analyses. At the same time, the representativeness is a distinct advantage of this novel dataset compared to existing nutritional studies of substitute products. So far, previous research has focused on selected products or brands (Bohrer, 2019; Chalupa-Krebzdak et al., 2018; Medici et al., 2023; Scholz-Ahrens et al., 2020), individual countries (Bryngelsson et al., 2022; Clegg et al., 2021; Farsi et al., 2022; Melville et al., 2023; Moshtaghian et al., 2024; Tonheim et al., 2022; Walther et al., 2022), or relied entirely on existing literature or data from commercial product databases (Petersen & Hirsch, 2023; Romão et al., 2023; Scholz-Ahrens et al., 2020; Silva & Smetana, 2022). With respect to market prices, such a comprehensive overview has so far been missing in publicly available literature, to the authors' knowledge.

The remaining article is structured as follows: The results section provides an overview of the nutritional properties and market prices found among the categories of meat and milk substitutes in the six studied countries and puts them in relation to conventional animal-sourced foods. Meat and milk substitutes were considered to be of highest interest because they are responsible for approximately 75 % of the total sales volume of substitutes in Europe (GFI Europe, 2023). Furthermore, many of the remaining categories (e.g., substitutes for cheese or eggs) do not contain sufficient records for a meaningful statistical analysis due to their limited availability in supermarkets today. The meat and milk results are directly compared to prices and nutritional properties of their animal-based benchmarks. The discussion section then links insights from the present study with publicly available consumption data and findings from consumer behavior studies. Key discussion points focus on i) advantages and remaining limitations of the available substitute products in comparison with conventional benchmarks, ii) the relevance of prices and nutritional properties for consumers, and iii) recommendations for further improvements.

2. Methods

2.1. Data collection

Product information including price per kilogram, product type (e.g., meat, milk), main ingredients, macronutrient, and where available micronutrient composition, were collected manually and semi-automatically from web shops of 13 major retailers in France (n = 3), Germany (n = 1), Italy (n = 2), the Netherlands (n = 2), Spain (n = 2), and the UK (n = 3) with the support of an open-source web scraping browser extension (Web Graph, 2023) (SI 2). The supermarket chains were selected based on their size and availability of online shops. The data collection took place in August 2023. All products were manually screened and classified based on their product type and main protein-rich ingredients (see also categorization). Several erroneous or incomplete entries were encountered during the manual screening. In these cases, if possible, the product information was collected from other sources such as websites of product manufacturers. Through this, missing nutritional information for 119 database entries could be added and 17 erroneous values were corrected. Erroneous entries that could not be corrected were removed as well as products in which substitutes are not the main component such as pastries and ready-made dishes. Certain products in the dataset occur multiple times because they were sold in several countries, different supermarkets of the same country, or as a chilled and unchilled version within the same supermarket. Since it was the goal of this data collection effort to provide a representative overview of the nutritional properties and the prices of the available product selection, these duplicates were not removed from the dataset. Prices of over 7500 conventional meat and milk products were collected in September 2023 from the same web shops to allow for a direct price comparison between animal-based benchmarks and substitutes (SI 4). Where indicated, prices provided in British pounds were translated into Euros based on the average exchange rate of 1.17 (GBP to EUR) during the two months of data collection (August-September 2023). The nutritional profile of animal-based benchmark products was averaged based on values obtained from food composition databases of Italy (Gnagnarella et al., 2022), the Netherlands (RIVM, 2021), the UK (Public Health England, 2021), and the US (USDA, 2023) (SI 3).

2.2. Categorization

Products were classified based on their main protein-rich ingredient(s) because the provision of protein is widely considered one of the key functions of animal-sourced foods in diets. The comparative analysis of nutrition and price between milk substitutes and conventional milk focused on non-flavored (plain) products. Among milk substitutes, the analysis focused on the most relevant types, which are oat, soy, almond, rice, coconut, coconut & rice, and oat & vegetable proteins. Meat substitutes were categorized based on their product type. The considered product categories include breaded products such as nuggets or cutlets, burger patties, meatballs, minced meat, sausages, deli meat, and whole cuts. The latter category includes minimally processed meat cuts such as roasts, steaks, and strips. As the name suggests, substitute products aim for a direct replacement of a specific benchmark product. For example, it is unlikely that a consumer replaces beef steak with vegan nuggets (Elzerman, Keulemans, Sap, & Luning, 2021; Michel, Hartmann, & Siegrist, 2021). Therefore, the price and nutritional composition of substitutes should be compared with benchmark products that have a similar dietary

role.

2.3. Fortification

The declaration of micronutrient contents on food labels is voluntary in the EU and UK except for fortified nutrients. Consequently, a large majority of the products that provide information about micronutrients in their label were fortified. In a prior screening among all products that reported micronutrient contents in their label, only 43 meat substitutes were identified that contained information about micronutrient contents although they were not fortified. Fortification rates were calculated for meat and milk substitutes by dividing the number of fortified products by the total number of products within each product category and country.

2.4. Data analysis

All data analyses were conducted in RStudio v. 2023.12.1 (Posit team, 2023). It was observed that statistical analyses of product prices could be strongly influenced by a few very highly or lowly priced products, e.g., expensive brands or products on sale. Therefore, outliers among substitute and benchmark products within a specific product category (e.g., cutlet substitutes or almond milk) were removed by the inter quartile range method prior to all price-related analyses (15 % of meat substitutes and 10 % of milk substitutes removed). Since nutrients are an inherent product property of interest, no outliers were removed prior to nutrient-related analyses. Only products with a full record of macronutrients were considered for statistical analysis (13 % of meat substitutes and 23 % of milk substitutes removed). The share of fortified products was calculated based on all data entries providing nutritional information and an ingredient list.

All distributions of prices and nutrient contents were skewed or non-Gaussian according to Kolmogorov-Smirnov tests. Thus, non-parametric two-sided Wilcoxon rank-sum tests were used at a 5 % significance level to test hypotheses throughout this study. For each country and product category, it was tested if prices of animal-sourced foods and substitutes are equal (null hypothesis) or different (Table S9 & S10). The same was done for each nutrient (Table S11 & S12). Further, it was tested for meat and plain milk substitutes, respectively, if fortified and non-fortified products are priced equally within one country (Table S13 & S14) and if prices of different milk substitutes differ significantly within the studied countries (Table S15 & S16).

3. Results

3.1. Overview of product variety

The sample included 975 meat and 758 milk substitutes. Of the meat substitutes, 65 % (n = 640) were produced from isolated or concentrated soy, pea, or wheat protein, or a mixture of those (labelled as mixed protein in Fig. 1a). Other relevant types included legume-, grain-, vegetable-, tofu-, and mycoprotein-based products. Thereby, the first three categories refer to minced or ground components such as pieces of vegetables or legume-based flour but no protein isolates or concentrates. Over 85 % of all meat substitutes found in this study were vegan. A relevant exception were mycoprotein-based products, which often rely on egg or milk powders as binders. Meatballs (10.5 % vs. 1.5 %), breaded products (14 % vs. 3.9 %), and burgers (18.1 % vs. 4.6 %) were overrepresented among meat substitutes compared to benchmark products found in the same supermarkets. Whole cuts (22 % vs. 36.5 %) and deli meat (10.2 % vs. 37.8 %), on the other hand, were strongly underrepresented (Fig. 1b). Milk substitutes were dominated by oat-, soy-, and almond-based products (Fig. 1a). The most common mixed milk substitutes included a combination of rice and coconut and oat-based products with added vegetable protein (e.g., pea).

3.2. Nutritional value

Most meat substitutes contained less energy, protein, total fats, and saturated fats than meat products of the same category such as burgers or breaded products. Exceptions were the energy content of whole cuts and meatballs, which were higher among substitutes. The meat

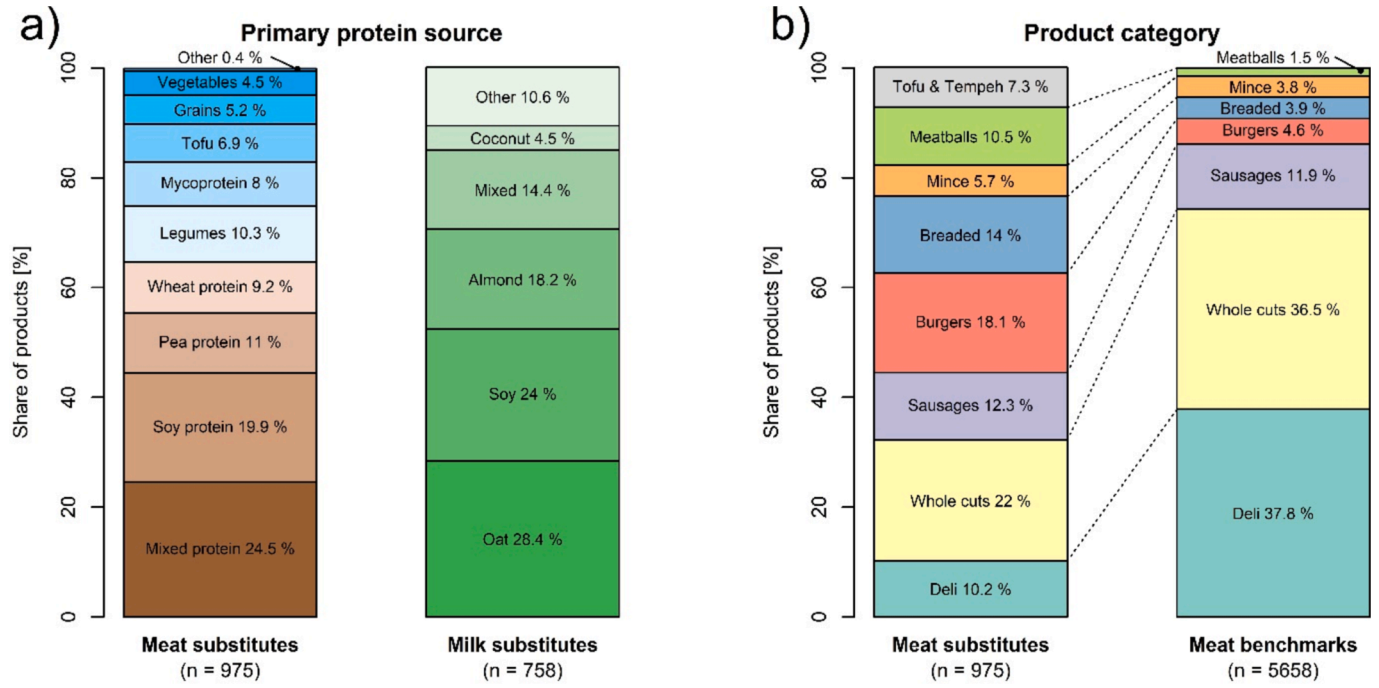


Fig. 1. Panel a) displays the share of meat and milk substitute products grouped by their main protein-rich ingredient. Mixed protein refers to meat substitutes that are based on a combination of protein isolates and/or concentrates from soy, pea, and wheat. Panel b) shows the share of meat substitutes and benchmarks grouped by product types. The percentages might not add up exactly to 100 percent due to rounding errors.

substitutes tended to have higher contents of carbohydrates and total sugar (except for sausages; Fig. 2a). In more processed categories; namely, breaded, burger, deli, meatballs, and sausage products, average substitute products reached between 1.5 and 5 times the carbohydrate and 0.9 to 4 times the sugar content of benchmarks. Compared to whole cuts or minced meat, which naturally contain almost no carbohydrates and sugar, carbohydrate and sugar contents of average substitute products could be 35 to 75 and 22 to 45 times higher, respectively. Similarly, salt content in the meat substitutes was comparable to processed meat, although much higher than that of whole cuts or minced meat. Substitutes that were entirely based on vegetables, legumes, and grains generally had protein contents below 10 % on a fresh-matter basis, while products based on mycoprotein, or concentrated plant proteins amounted to about 10 to 20 % protein. The meat substitutes

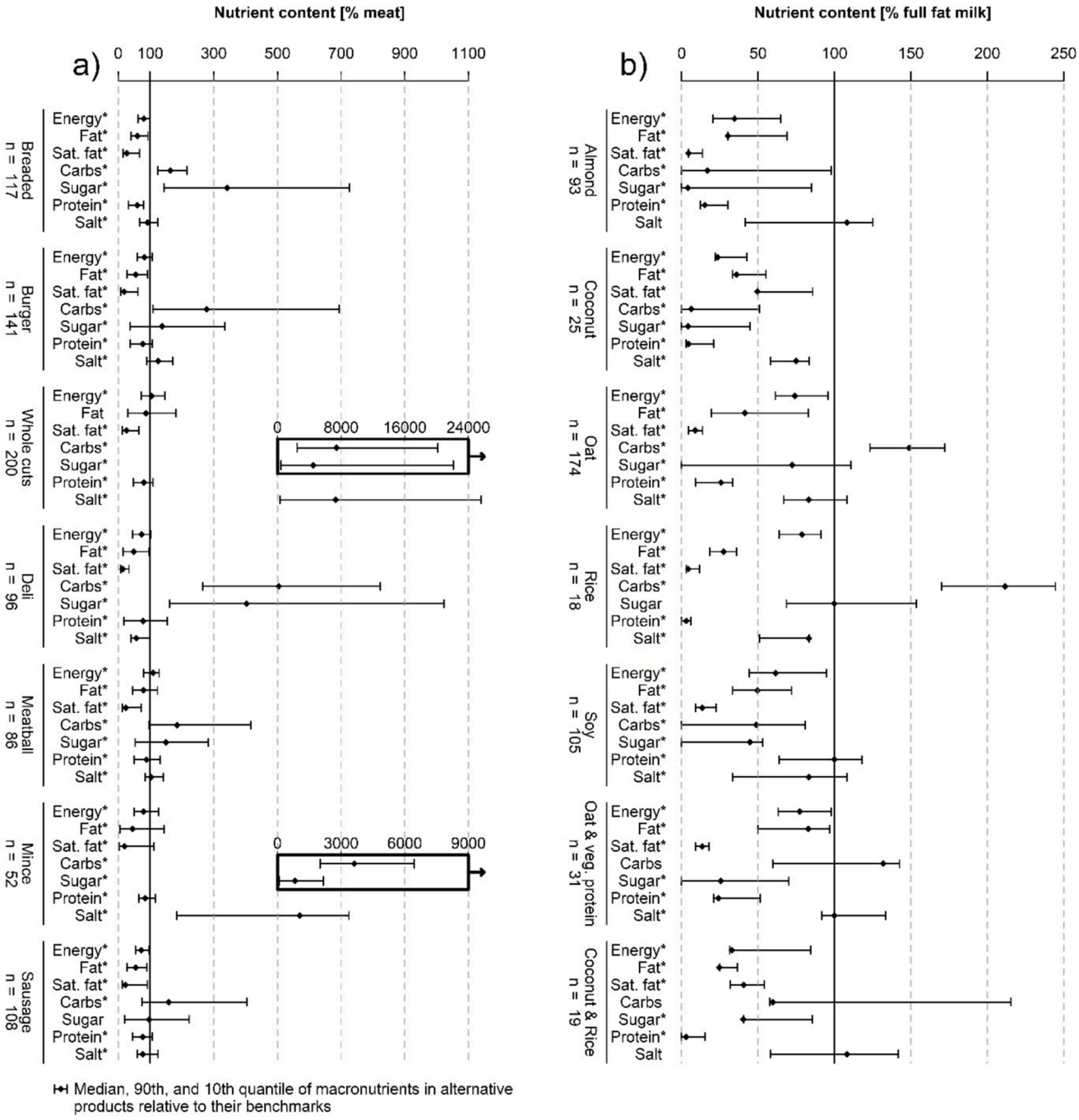


Fig. 2. Nutrient profiles of meat- and plain milk substitutes relative to their respective animal-based benchmarks grouped by product type (meat) and main ingredient (milk). The benchmark values are averages of the respective product category found in major food composition databases and set to 100 % (the vertical lines). The nutrient contents of substitute products are expressed in percent of the average benchmarks and shown as median values together with the 90th and 10th quantiles. All values are considered before cooking. Relative values for carbohydrate and sugar contents of whole cut and mince substitutes are extremely high because the benchmark products contain almost none of these nutrients. In absolute terms, the median values for carbohydrates in whole cuts and mince substitutes are 4.8 and 4.3 g/100 g, respectively. For sugar, the median values are 1 and 1 g/100 g, respectively. Comparable benchmark products generally contain neither carbohydrates, nor sugar and if they do, their contents are well below 1 g/100 g. For the milk substitutes, only non-flavored products were considered and compared to non-flavored, full-fat benchmarks. An asterisk behind the nutrient label indicates a significant difference between the sample of substitutes and average benchmark values ($p < 0.05$). Exact values are provided in Tables S. 1–3 & S. 11–12.

mean dietary fiber content was 4.87 ± 2.15 g per 100 g in comparison to conventional meat, which contained no dietary fiber (Table S1).

Milk substitutes based on almonds and coconuts contained a significantly lower amount (< 50 % on average) of total energy, fat, carbohydrates, sugar, and protein compared to full fat cow's milk (Fig. 2b). The almond-based products contained very low amounts of saturated fat, while coconut-based drinks showed the highest levels among all milk substitutes reaching 50 – 80 % of saturated fat contents found in the full fat milk. Grain-based products had lower energy, fat, and protein content but exceeded the level of carbohydrates usually found in cow's milk. Most oat-based milk substitutes contained less sugar than cow's milk, while the rice-based products showed an opposite tendency. All soy-based milk substitutes had lower levels of total energy, and all considered macronutrients, except for protein, which often matched or even exceeded the contents found in full fat milk. The salt contents of milk substitutes were on a similar level as in full fat milk products. Compared to conventional milk, substitutes contained small amounts of dietary fiber with an average of 0.64 ± 0.36 g per 100 g (Table S2).

Overall, 27, 22, and 6 % of the meat substitutes were fortified with vitamin B12, iron, and zinc, respectively. In comparison to meat substitutes, milk substitutes were fortified more frequently. Overall, 62, 53, 50, 43, and 8 % of milk substitutes were fortified with vitamin D, vitamin B12, calcium, vitamin B2, and vitamin E, respectively. The average contents of fortified substitutes and the corresponding benchmarks as well as dietary reference values are shown in Table 1.

Interestingly, there were notable differences regarding the share of fortified meat and milk substitutes depending on the product type and main protein-rich ingredient. Fortification of meat substitutes was more common among products that aim to replace less processed meat such as whole cuts or mince while fortified substitutes for sausages or deli meat were more difficult to find (Fig. 3b). Further, products based on concentrated or isolated soy and mixed plant proteins (e.g., soy and wheat protein in combination) were more frequently fortified than, e.g., products that had wheat gluten or mycoprotein as their only main protein source (Fig. 3c). Among milk substitutes, almond-, oat-, soy-, and oat-based products with additional vegetable protein were frequently fortified with vitamin B2, in contrast to rice- and coconut-based drinks (Fig. 3a). Almond-based drinks were the only product category that was frequently fortified with vitamin E. Calcium, vitamin B12, and vitamin D were frequently fortified across all plant-based milk substitutes. For these nutrients, rice-based products and mixtures from rice and coconut showed the lowest fortification rates. It should be noted that cow's milk is not a relevant natural source of vitamin D either (Table 1). Therefore, it is also fortified with vitamin D in certain countries.

The level of product fortification varied among the considered countries (Fig. 3d). France had a particularly low share of fortified milk substitute products, while the Netherlands showed the highest fortification rates among meat and milk substitutes. The remaining countries were approximately on the same level in both categories, respectively.

3.3. Product prices

Fig. 4 shows the product prices for meat substitutes (Panel A) and plain milk substitutes (Panel B) and their corresponding benchmarks grouped by country and product type (see also S.2 in SI1). It is evident that substitutes tend to be more expensive in most countries. This was largely confirmed by the conducted Wilcoxon rank-sum tests (Fig. 4). Exceptions could mainly be found in the categories of meatballs and minced meat as well as among rice- and soy-based milk substitutes (Fig. 4). To estimate the price gap, a country-specific price ratio between substitutes and benchmarks was calculated. For milk substitutes this was calculated by averaging the price of all milk substitutes, then dividing it by the average price of all milk products in each country. In the case of meat substitutes and conventional meat, the average ratio was first calculated for each product category separately to avoid that price differences in one category (e.g., deli meat) are too dominant. Subsequently, a weighted average was taken based on the number of substitute products in each category. The lowest price ratio for meat substitutes and their corresponding benchmarks was 0.95 for Germany. In other words, meat substitutes were on average slightly cheaper than benchmarks of the same product category in the German retailer. In Spain, the average price ratio was highest with a value of 2.15. In the remaining countries, it was between 1.24 and 1.46. The average price ratios of milk substitutes in comparison with full fat milk were all between 1.35 (Germany) and 1.58 (France & Italy).

As mentioned above, some of the substitutes were fortified with micronutrients, while others were not (Fig. 3). Since meat substitutes should be compared for each product group individually, resulting sample sizes of fortified products were often very small (Table S13). Therefore, a direct price comparison of fortified and unfortified products was often impossible, particularly in Italy and Spain. Nevertheless, the data indicates that fortified meat substitutes on average tend to be more expensive in the UK but cheaper in the Netherlands compared to unfortified products of the same category (e.g., deli meat; Table S13). Fortified milk substitutes were significantly more expensive ($p < 0.05$) in Germany and Spain compared to unfortified products (Table S14). For all other countries, no significant difference ($p > 0.05$) could be found. However, it should be noted that the mean price of fortified milk substitutes was 10 % below the mean price of unfortified milk substitutes in the Netherlands.

4. Discussion

Gathering product information on meat and dairy substitutes and

Table 1
Mean concentrations of micronutrients in fortified substitutes and animal-based benchmarks. The two last columns show population reference intakes provided by the European Food Safety Authority (EFSA) for males and non-pregnant, non-lactating, menstruating women above the age of 25, respectively (European Food Safety Authority, 2017). See also Tables S3 & S5. It should be noted that bioaccessibility and bioavailability of nutrients can be different between plant- and animal-based foods. Cells that contain "NA", i.e., not applicable, indicate that no meat or milk substitutes were fortified with this micronutrient.

	Meat substitutes	Meat	Milk substitutes	Full-fat cow milk	EFSA PRI males*	EFSA PRI females*
Vitamin B2 [mg/100g]	NA	0.15–0.29	0.21±0.02	0.19	1.6	1.6
Vitamin B12 [μg/100g]	0.68±0.36	0.59–2.67	0.40±0.11	0.45	4.0	4.0
Calcium [mg/100g]	NA	7.61–62.6	121±16.1	118	950	950
Vitamin D [μg/100g]	NA	0.3–0.78	0.87±0.23	0.01	15**	15**
Vitamin E [mg/100g]	NA	0.17–0.78	2.03±1.54	0.05	13***	11***
Iron [mg/100g]	3.70±1.77	0.89–2.08	NA	0.1	11	16****
Zinc [mg/100g]	1.64±0.54	1.98–2.94	NA	0.4	9.4–16.3	7.5–12.7

*reference intakes are given in mg or μg per day instead of per 100g of product
**under minimal cutaneous vitamin D synthesis. Requirements could be lower in the presence of endogenous cutaneous vitamin D synthesis
***values refer only to alpha-Tocopherol
****decreases to 11 after menopause

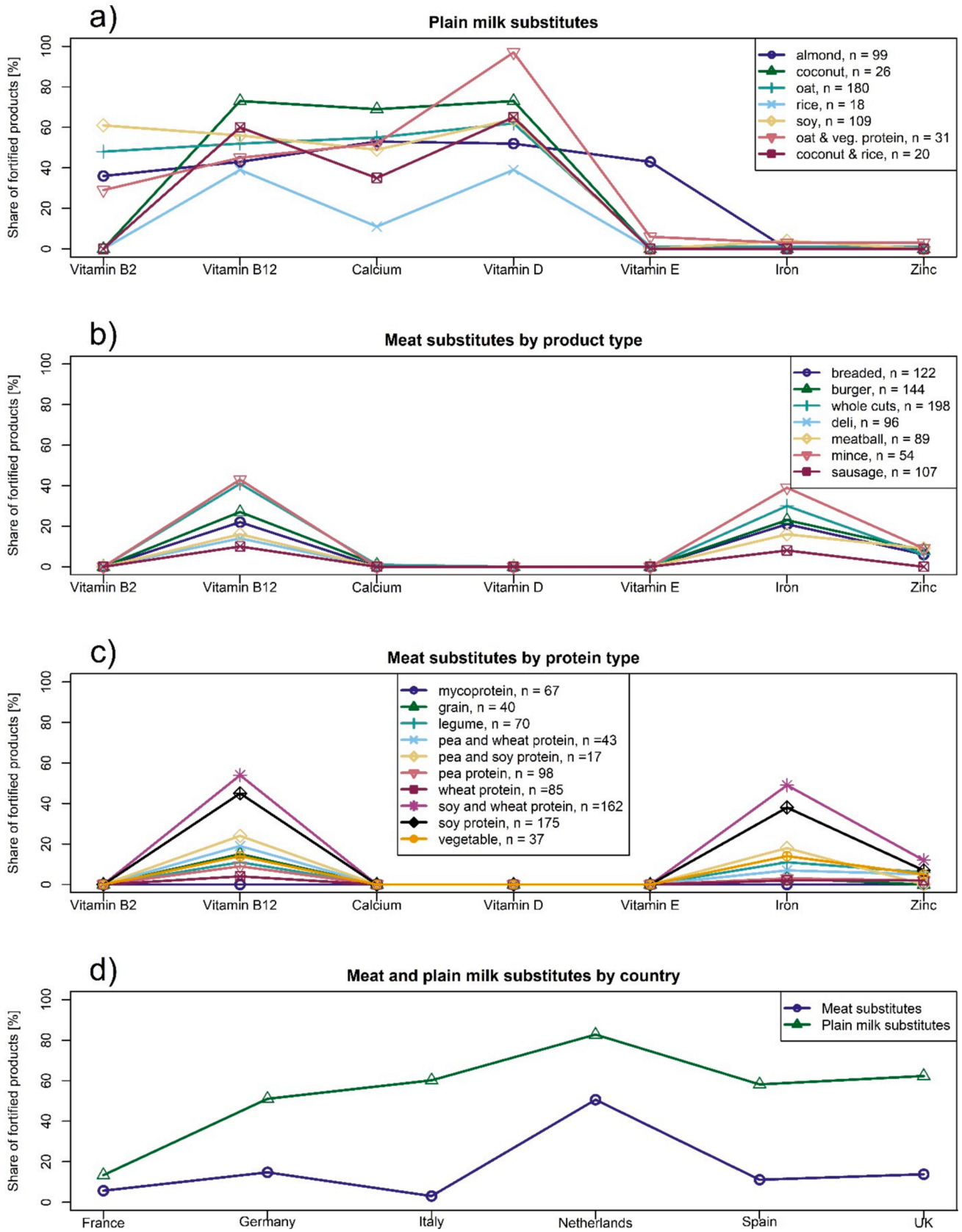


Fig. 3. Share of plain milk (a) and meat (b & c) substitutes that are fortified with specific micronutrients. Panel d) shows the share of meat and milk substitutes fortified with at least one micro-nutrient for each country. Exact values are provided in Table S5 & S6.

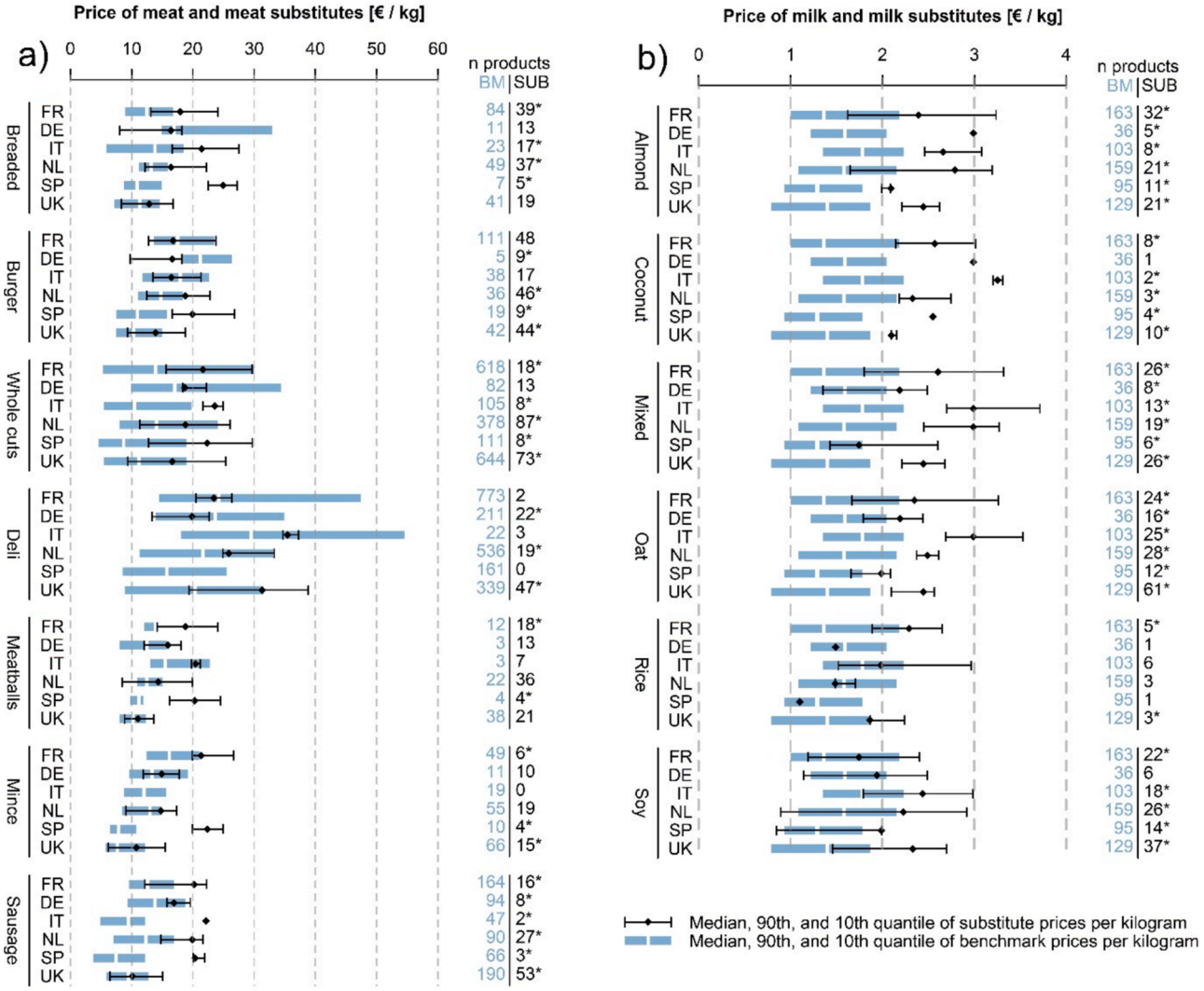


Fig. 4. Prices (in €) per kilogram of a) meat and b) milk substitutes (SUB) and their respective benchmarks (BM) available in online shops of major supermarket chains in France, Germany, Italy, the Netherlands, Spain, and the UK. An asterisk behind the number of identified products indicates a significant price difference between BMs and SUBs ($p < 0.05$). Exact values are provided in Tables S. 7–10.

their animal-based benchmarks from large European supermarket chains allowed for a direct comparison between regularly sold substitute and benchmark products based on their nutritional quality and price. In general, the presented nutritional information for meat and milk substitutes (Fig. 2a&b) aligns well with previous research (Bohrer, 2019; Bryngelsson et al., 2022; Chalupa-Krebzdak et al., 2018; Clegg et al., 2021; Farsi et al., 2022; Ketelings et al., 2023; Medici et al., 2023; Melville et al., 2023; Moshtaghian et al., 2024; Scholz-Ahrens et al., 2020; Tonheim et al., 2022; Walther et al., 2022). At the same time, it adds to current knowledge by depicting the large diversity of nutritional profiles among products that European consumers can choose from within distinct product categories, e.g., almond drinks or meatball substitutes. Further, the data provides a comprehensive overview of fortification rates among substitute products in the European market. Meanwhile, information on the pricing of substitute products has been lacking entirely at a European level. Hence, the presented data contributes to a deeper understanding of strengths and limitations of substitute products in comparison with animal-based benchmarks in two key domains: nutritional quality and affordability.

Against the background of widespread overconsumption, excess intakes of saturated fats, and inadequate intakes of dietary fiber in European diets (Breda et al., 2020), meat substitutes can provide nutritional benefits. This is particularly among processed categories such as burgers, sausages, or breaded products, where also a large variety of substitutes is available (Fig. 1). On average, the consumption of 100 g of a meat substitute covers almost 20 % of the recommended 25 g daily fiber intake for adults (European Food Safety Authority, 2017), and increased consumption of this nutrient is associated with positive health outcomes (Barber et al., 2020). Although substitutes tend to have lower protein contents, there are items in each category, except for breaded products, that match the average protein content of the benchmarks. Besides containing a similar amount of total protein, it is also essential for meat substitutes to provide a similar protein quality compared to benchmark products. Protein quality is commonly assessed by the digestible indispensable amino acid score (DIAAS). Over 50 % of the available products are based on soy protein, pea protein, or a mixture of soy, pea, and wheat protein. On an ingredient level, soy and pea proteins were found to have a DIAAS of 90 and 82 (Rutherfurd et al., 2015), respectively, when compared to dietary requirements of children (0.5–3 years), who have more stringent requirements than adults. Further, a mixture of pea (25 %), wheat (20 %), and soy protein (55 %) showed a DIAAS of 90, compared to dietary requirements of children (0.5–3 years) (Herreman et al., 2020). Although values were slightly below the DIAAS of animal-sourced proteins, they are still indicative of high-quality proteins. However, these findings should be confirmed by DIAAS measurements of the final substitute products. Several other widely used

protein-rich ingredients such as wheat protein, mycoprotein, and grains have significantly lower DIAAS scores (Ariëns et al., 2021; Han et al., 2019; Herreman et al., 2020). They are thus not an equivalent replacement for animal-sourced protein without complementary protein sources on the menu or products that combine different plant material to reach complete DIAAS scores. An alternative option to increase protein quality could be the formulation of hybrid products that contain both plant- and animal-based protein. Further, attention must be paid to significantly higher sugar (up to ~ 5 g / 100 g in burger and whole cut substitutes) and salt (up to ~ 3 g / 100 g in deli substitutes) contents among certain substitute products (90th percentile in Fig. 2a). Direct comparisons for the latter are difficult because the higher salt content in substitutes is often linked to pre-marinating, while meat products are often salted by the consumer. Excessive sugar and salt contents have been associated with severe health risk and should be avoided (Breda et al., 2020). According to recommendations from the world health organization (WHO), the intake of free sugars should be less than 5 – 10 % of total energy intake (World Health Organization, 2015), and salt consumption should not exceed 5 g / day (World Health Organization, 2012).

While milk substitute formulations show reduced saturated fat and elevated dietary fiber contents, none of the available products can match protein contents of cow's milk, except for certain soy-based drinks (Fig. 2b). Furthermore, DIAAS scores of all products apart from soy-based drinks are far below 100 for children, adolescents, and adults (Walther et al., 2022), suggesting that only soy-based products have the potential to provide adequate macronutrients to consumers when consumed as a substitute for milk.

Information on the micronutrient composition was almost exclusively limited to fortified substitutes, which is a drawback of the used approach. This is because most product labels do not provide micronutrient concentrations unless they are fortified. However, the few meat substitutes, which do not report any fortification but still do provide nutritional information on micronutrients demonstrate that iron contents of unfortified products can reach similar levels (3–5 g / 100 g) as found in fortified products (see SI2). These values are even two to three times higher compared to average iron contents of meat (Table S3). However, it must be considered that iron absorption is strongly influenced by dietary components and is often limited in plant-based foods due to the presence of phytates and polyphenols, which inhibit the uptake of non-heme iron (Ems et al., 2023). For example, it was found that only 5–12 % of iron could be absorbed from vegetarian diets compared to 14–18 % in mixed diets (Hurrell & Egli, 2010). Consequently, it was recommended for vegetarians to increase iron intake by 80 % compared to nonvegetarian diets (Hunt, 2003). Zinc is another nutrient with lower absorption values. The bioavailability of zinc can be limited in plant-based foods due to the presence of phytic acid; accordingly, the zinc intake in vegetarian diets should be increased by 50 % to account for this (Hunt, 2003). Several food-processing practices are known to reduce the phytate content of plant-based foods and thereby increase the absorption of iron and zinc (Gibson et al., 2018). Some of them are already standard techniques in the manufacturing of meat substitutes such as milling of cereals and extrusion cooking. At the same time, research and industry turn toward fermentation as a method to improve the nutritional and sensory properties of modern meat substitutes (Elhalis et al., 2023a, 2023b). Another relevant micronutrient in substitute products is vitamin B12. Animal-based foods are its main source in the human diet because plants naturally lack this vitamin (Watanabe, 2007). Hence, if meat substitutes should become a widely used alternative to conventional meat products, the low fortification rate of available meat substitutes in France, Germany, Italy, Spain, and the UK (Fig. 3d) is critical to address if these micronutrients are not supplied in other ways (e.g., through supplementation). Of the countries studied, only the Netherlands had relatively high fortification levels. Additionally, the higher prices for fortified products as observed for the UK (Table S13) could force consumers to make trade-offs between affordability and nutritional value. As recent research has shown, expected costs are often perceived as a barrier to consuming healthy and sustainable food. Therefore, consumers are unlikely to be willing to pay more for fortified products (Embling et al., 2024).

For plant-based milk substitutes, the primary ingredients also contain high amounts of certain micronutrients. For example, almonds are rich in calcium, iron, zinc, and vitamin B2 (USDA, 2022). The main problem is, however, that these ingredients are strongly diluted during the production of milk substitutes. Their final concentration reaches a maximum of 10 – 15 % (see SI2). Consequently, calcium and vitamins B2 and B12 are far lower in the final product compared to cow's milk (Walther et al., 2022). This lack of multiple essential micronutrients in comparison with conventional milk might explain the high fortification rates among milk substitutes (Fig. 3). Nevertheless, a significant share of products remains unfortified and is thus an inadequate replacement for conventional milk from a micronutrient perspective. In consequence, a large-scale substitution of milk by currently available substitutes could lead to reduced micronutrient intakes among consumers, if they do not properly supplement with other measures; accordingly, educating consumers would be important (Green et al., 2022). As with meat substitutes, higher prices for fortified milk substitutes might discourage consumers from buying more nutritious products in Germany and Spain (Table S14).

Overall, despite certain benefits like lower saturated fat and higher fiber contents, a substantial replacement of animal-sourced foods with substitutes should be planned carefully. For example, it was found that a vegan diet frequently leads to low protein and vitamin B2 intake and deficiencies in vitamin B12, zinc, calcium, and selenium (Bakaloudi et al., 2021). Hence, if substitute products are adopted on a large scale, the nutritional composition of most available products needs to be further improved with a focus on high-quality protein and micronutrient supply. This could be achieved by a combination of complementary plant-based protein-rich ingredients and fortification. Another solution might be the incorporation of novel ingredients and technologies with promising nutritional benefits such as microalgae (Caporgno & Mathys, 2018) or precision fermentation (Chai et al., 2022).

In addition, emphasis must be placed on raising awareness among consumers about the relevance of nutritional quality and healthiness of substitute products. Fig. 3d indicates that a substantial proportion (20 – 90 % depending on the country and product category) of substitute products are not fortified. With such a large availability of unfortified products, it is likely that consumers select unfortified over fortified substitutes if they do not consider nutritional value in their purchasing decision. As discussed above, higher mean prices for fortified substitutes may even provide an incentive to choose unfortified products in certain countries. This is in line with findings from a focus group study about novel fortified foods in which UK consumers identified trade-offs between taste, health, price, and familiarity for fortified foods (Embling et al., 2024). While positive perceptions of health benefits led to increased willingness to buy, cost and uncertainty about product use were mentioned as potential barriers.

Health awareness also plays an important role in the perception of meat substitutes such that meat substitutes were perceived to be healthier than meat products (Ketelings et al., 2023). Ketelings et al., 2023 found that consumers expect meat to contain less salt than meat substitutes, more saturated fat than meat substitutes, and do not expect meat to contain more fiber than meat substitutes. Hence, in this respect, consumer expectations seem to match the current market situation as presented in this study (Fig. 2). At the same time, Ketelings et al. 2023 concluded that consumers tend to overestimate the protein content of meat substitutes relative to meat. This underlines the importance of developing meat substitutes that match their animal-based counterparts not only with regard to taste and price, but also protein and micronutrient contents considering differences in bioaccessibility and bioavailability.

According to the presented data (Fig. 4a&b), certain meat substitutes

as well as rice- and soy-based milk substitutes can already be cheaper compared to benchmarks of the same product category. In general, however, European consumers still pay an average premium between 24 and 58 % for meat and milk substitutes, whereas premiums for milk substitutes tend to be higher compared to meat substitutes in the same country. Exceptions were found for the German retailer where price parity between meat substitutes and benchmarks has been reached and one Spanish retailer where the average price premium for meat substitutes remains at over 100 %.

For the substitutes to become more competitive, prices should at least decrease to the level of comparable benchmarks. While industry experts anticipate a continuous decrease in product prices with increasing optimization and scaling effects (Witte et al., 2021), the uneven distribution of agricultural subsidies in the European Union (EU) still poses a major barrier for substitute products to reach price parity. It was recently estimated that over 80 % of payments under the Common Agricultural Policy of the EU were directly or indirectly supporting animal-based products (Kortleve et al., 2024). At the same time, product prices are only one of many factors that influence consumer's willingness to purchase substitute products (Hansen et al., 2023; Hartmann & Siegrist, 2017). This is nicely illustrated at the example of milk substitutes. Soy-based drinks are not only more nutritious compared to oat- and almond-based products but, in most countries, also significantly cheaper (Fig. 2b; Table S15 & S16). Nevertheless, soy-based drinks have recently lost market shares to almond- and oat-based drinks in all studied countries (no detailed data is available for the UK; Table S17) (Smart Protein, 2021). It is likely that sensory properties are responsible for this trend as soy-based substitute products are associated with beany off-flavors (Fiorentini et al., 2020; Short et al., 2021; Waehrens et al., 2023). Other factors could be the allergenicity of soy (L'Hocine & Boye, 2007) and its perceived association with high environmental impacts (Siegrist & Hartmann, 2019).

Sensory properties and particularly functionality can be expected to be even more dominant in the decision making of consumers when it comes to meat substitutes, because the types of meat products and their dietary roles are very diverse (Elzerman, Keulemans, Sap, & Luning, 2021; Michel, Hartmann, & Siegrist, 2021). Yet, the number of available meat substitutes is only slightly higher than for milk substitutes (Fig. 1). Hence, for the time being, potential consumers are probably primarily concerned about finding a product that satisfies their expectations for taste and functionality before distinguishing between equally satisfying products by price. This is particularly relevant for the segments of whole cuts and deli meat, which are largest among benchmark products but clearly underrepresented among substitutes (Fig. 1). Consequently, there are currently no suitable substitutes for many occasions where Europeans are used to consuming meat, especially when whole cuts of meat would be used (Elzerman, Keulemans, Sap, & Luning, 2021; Michel, Hartmann, & Siegrist, 2021). Hence, for a large-scale adoption of meat substitutes, it will be crucial that producers allocate their resources more towards the development of products that match sensory and nutritional properties of meat cuts and deli meat. This also has far-reaching consequences from an environmental sustainability point of view. In general, substituting meat with alternative protein sources is a promising approach to reduce environmental impacts of food systems (Green et al., 2022; Smetana et al., 2023). However, if substitute manufacturers and retailers are not able to provide suitable replacements for the main segments of meat products (Fig. 1), the environmental benefits will remain limited.

5. Conclusions

This comprehensive data set is expected to be a useful resource for future research such as nutritional studies, or dietary and economic modelling, which require a representative overview of available substitute products on the European market and their characteristics. The presented results and arguments highlight the need to further improve the nutritional value of meat and milk substitutes, particularly in terms of protein quality and micronutrient contents. At the same time, more digestibility assessments on a final product level are needed to allow for a more accurate comparison of protein and micronutrient quality in substitutes and benchmarks. The price gap between substitutes and benchmarks remains significant in most European countries, and consumers are facing trade-offs between affordability and nutrition in certain countries due to higher prices being charged for fortified products. While price parity should be achieved to attract more consumers, other factors like taste and functionality are likely also relevant in consumer's purchasing decisions. Finally, companies should focus on the production of high-quality substitutes for deli meat and whole cuts to target the main drivers of meat production and increase environmental sustainability.

CRediT authorship contribution statement

Armin Siegrist: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Ashley Green:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Fabienne Michel:** Writing – review & editing, Conceptualization. **Alexander Mathys:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Funding

This work was supported by the European Union's Horizon Europe Research and Innovation program under grant agreement no. 101059632 project GIANT LEAPS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank Dr. Paride Azzari for his valuable input regarding data analysis. The graphical abstract was created using biorender.com.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodres.2024.115213.

Data availability

All data is made available in the supplementary information.

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