Food Chemistry 448 (2024) 139059

Contents lists available at ScienceDirect

Food Chemistry

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

A comparative analysis of nutritional quality, amino acid profile, and nutritional supplementations in plant-based products and their animal-based counterparts in the UK

Liangzi Zhang, Ellie Langlois, Katie Williams, Noemi Tejera, Maja Omieljaniuk, Paul Finglas, Maria H. Traka *

Food and Nutrition National Bioscience Research Infrastructure, Quadram Institute Bioscience, Norwich Research Park, Rosalind Franklin Rd, Norwich NR4 7UQ, United Kingdom

ARTICLE INFO

Keywords:
Plant-based products
Meat alternatives
Nutritional quality
Nutri-score
Amino acids

ABSTRACT

Plant-based (PB) food products have surged in popularity over the past decade. Available PB products in the UK market were extracted from NielsenIQ Brandbank and compared with animal-based (AB) counterparts in their nutrient contents and calculated Nutri-Scores. The amino acid contents of four beef products and their PB alternatives were analysed by LC-MS/MS. PB products consistently exhibited significantly higher fibre content across all food groups. Protein was significantly higher in AB products from all food groups except beef and ready meals. PB products were more likely to have higher Nutri-Scores compared to AB counterparts, albeit with greater score variability within each food group. Nutrient fortifications were primarily focused on dairy and ready meals; the most supplemented nutrient was vitamin B12 (found in 15% of all products). A higher proportion of EAAs in relation to total protein content was observed in all beef products.

1. Introduction

Due to the rapid global population growth and the anticipated strain on the world's food supply, it is projected that by 2050, there will be a 44% increase in the demand for animal-based (AB) products to meet the current global consumption trends (Niklewicz et al., 2023). Nevertheless, the livestock industry places substantial demands on resources and contributes significantly to issues like global warming and pollution (Santo et al., 2020). A shift to a more sustainable dietary pattern that reduces or eliminates the consumption of AB foods has the potential to decrease water usage in food production by 50% and reduce both land utilization and greenhouse gas emissions by up to 80% (Aleksandrowicz, Green, Joy, Smith, & Haines, 2016). Along with the widespread malnutrition concerns, including obesity, undernutrition, and other dietary risks (Swinburn, Kraak, Allender, Larijani, & Tootee, 2019), and the inequitable distribution of resources around the world, these combined pressures have prompted the formulation of numerous scientific objectives concerning balanced diets and sustainable food production. The EAT-Lancet Commission and the World Health Organization have both established that guiding populations towards wholesome plant-based (PB) diets featuring fewer AB foods could yield substantial positive effects on human, animal, and environmental health (Willett et al., 2019).

A diet centred around PB foods is often characterized by a high intake of dietary fibre and bioactive compounds sourced from fruits, vegetables, whole grains, nuts, and seeds. This dietary approach typically entails reduced consumption of animal fats and proteins (McMacken & Shah, 2017). There exists widespread acknowledgment that such a dietary regimen, coupled with a limited intake of salt, saturated fats, and added sugars, is strongly correlated with a decreased likelihood of premature mortality and provides a protective effect against noncommunicable diseases (NCDs). In more specific terms, beneficial impacts have been found in different aspects of health, especially in developed countries, including weight management, lowered blood pressure and cholesterol levels, mitigation of atherosclerosis, management of type II diabetes, and a potential reduction in the risk of certain cancers, including prostate and colon cancer (Domic, Grootswagers, van Loon, & de Groot, 2022; Sterling & Bowen, 2019).

* Corresponding author.
E-mail addresses: Liangzi.zhang@quadram.ac.uk (L. Zhang), ntejera@ebi.ac.uk (N. Tejera), paul.finglas@quadram.ac.uk (P. Finglas), maria.traka@quadram.ac.uk (M.H. Traka).

https://doi.org/10.1016/j.foodchem.2024.139059
Received 22 December 2023; Received in revised form 14 March 2024; Accepted 15 March 2024
Available online 21 March 2024

The recognition of the positive effects on both health and the environment has resulted in a notable increase in the number of individuals adopting a PB diet. Up until July 2022, data from the YouGov tracker revealed that 2–3% of the population in the UK identified as vegan, and 63% of them started the diet only in the last five years. Around 5–7% classify themselves as various types of vegetarians ("Dietary choices of Brits (e.g. vegeterian, flexitarian, meat-eater etc),", 2023). This trend has powered the emergence of PB alternatives in the market over the past decade (Kim et al., 2021). The analysis of the National Diet and Nutrition Survey 2008–2019 revealed that the consumption of PB products between 2008 and 2011 and 2017–2019 doubled in the UK (Alae-Carew et al., 2022). A substantial portion of these alternatives are recognized as meat analogues, known for their convenience in preparation and their ultra-processed nature (Bohrer, 2019; Flint, Bowles, Lynn, & Paxman, 2023). The European Consumer Survey on Plant-based Foods reported that the United Kingdom holds the highest rates of purchase and consumption of PB products across categories like milk, meat, butter/margarine, cheese, ready meals/food-to-go, and seafood, compared to other European countries (*European consumer survey on plant-based foods - describing the product landscape and uncovering priorities for product development and improvement,* 2020). While not all ultra-processed foods are necessarily unhealthy, it was found that a significant proportion of plant-based products have higher energy density, sodium, saturated fat, and free sugars while lacking in dietary fibre when compared to unprocessed and minimally processed PB foods (Brooker, Hendrie, Anastasiou, & Colgrave, 2022; Gehring et al., 2021).

Furthermore, it is widely acknowledged that strict PB diets, including vegan diets, generally offer a limited supply of specific essential nutrients. These include protein, omega-3 fatty acids, vitamin B2, B3, B12, vitamin D, iron, zinc, calcium, potassium, selenium, and iodine (Bakaloudi et al., 2021; Weikert et al., 2020). However, due to the diverse range of existing PB products and the limitations of available data on the content of vitamins and minerals, it's a complex task to evaluate the sufficiency of these nutrients in current PB products (Bryngelsson, Moshtaghian, Bianchi, & Hallström, 2022). Previous studies have employed different methods to estimate the micronutrient compositions of PB products within various national markets. These methodologies include approaches such as recipe calculations (L. Harnack et al., 2021), chemical analysis (Ložnjak Švarc et al., 2022), and the compilation of fortified nutrient information (D'Andrea, Kinchla, & Nolden, 2023). These studies were more focused on either particular food groups or a limited selection of individual PB products.

Given that our understanding of the nutritional profiles of PB products is still limited, it is important that further research be undertaken to comprehensively assess the nutritional quality of these products in relation to their AB counterparts (Wickramasinghe et al., 2021). This is crucial to engaging stakeholders, policymakers and the food industries to improve the quality of these products that can contribute towards better health and the environment, as well as empower consumers to make informed dietary choices. The present study sets out to do a multifaceted examination of the majority of the PB products available in the UK market in contrast to conventional AB products. Specifically, the study aims to evaluate the nutritional compositions of PB products, their Nutri-Scores as an indicator of overall nutritional quality, and the scope of nutrient supplementation in these products. Furthermore, chemical analysis of the amino acid compositions was conducted across four beef products and their corresponding PB alternatives. The findings were examined, in conjunction with other established references, for their potential implications for human health.

2. Materials and methods

2.1. Data gathering

The back-of-pack nutrient information for all available PB products in the UK market up until 26th May 2022 was sourced and extracted from NIQ Brandbank © 2022. NIQ Brandbank holds the largest central repository of grocery products (including foods) in the UK and covers 98% of the existing products. The following key terms were searched in the Brandbank database: including 'plant-based', 'vegan', 'vegetarian', 'meat-free', plus a list of PB ranges from major supermarkets and commercial brands that manufacture PB products. A total of 2695 products were downloaded for further product screening. Product information relevant for the study was extracted, including food name, portion size, food group and subgroup, ingredient list, nutrient information for both per 100 g and per portion. Products with empty nutritional information were excluded from the analysis.

2.1.1. Back of pack nutrient analysis

Products falling into the following categories were grouped together manually and extracted from the PB products database, including fish ($n = 22$), chicken ($n = 104$), beef ($n = 197$), sausages ($n = 105$), cheese ($n = 51$), milk ($n = 33$), and ready meals ($n = 446$). The nutrient contents from the product labels were compared to the nutrient contents of the corresponding ten generic AB products in each food group. The nutrient information for the AB products was sourced from the UK Composition of Foods Integrated Dataset (Composition of Foods integrated dataset, 2021), with the exception of ready meals, where the AB products chosen for comparisons were popular selections available in UK supermarkets. The nutrients available in the back-of-pack nutrition labels were used for comparisons with those from the AB counterparts, including energy, fat, saturated fat, carbohydrates, sugars, fibre, protein, and salt.

2.1.2. Nutri-Score

The Nutri-Score algorithm was developed to thoroughly evaluate the nutritional quality of food products, considering both nutrients and the inclusion of beneficial food groups. It has been widely adopted in various European countries and is prominently displayed on the packaging of many food items. A Nutri-Score for each product from both PB and AB categories was computed from an in-house Nutri-Score calculator, which was developed based on the algorithm outlined by the French Ministry of Health (van der Bend, van Eijsden, van Roost, de Graaf, & Roodenburg, 2022). The inputs of the calculator include nutrient contents per 100 g of product, energy (kJ), saturated fat, sugars, fibre, protein, and salt. The percentage of 'fruits, vegetables, pulses, nuts, and rapeseed, walnut, and olive oils' is also one of the contributors to the final score; however, the percentages of ingredient contributions were frequently absent in most products, hence it was not included in this particular analysis. The outcome of this computation is a letter grade ranging from A to E, with A denoting the highest nutritional value and E representing the lowest nutritional value.

2.1.3. Nutrient supplementations

The type and scope of nutrients supplemented in the products were summarized in PB products. This analysis was based on all PB products downloaded from the Brandbank database (excluding products without nutrient information) separated in food groups predefined by the database. The nutrient contents of supplemented nutrients are normally listed on the nutritional labels of products. The main nutrients identified in the downloaded products include vitamin B12, calcium, vitamin D, iron, vitamin B2, vitamin E, other Vitamin Bs (niacin, thiamine, and vitamin B6), vitamin A, vitamin C, and other vitamins (vitamin K, biotin, and Pantothenic acid).

2.2. Amino acid analysis of beef and PB beef products

Proteins consist of amino acids linked by peptide bonds and are categorised as essential, conditionally essential, or non-essential. According to the nutrient comparison results, PB and AB products from the beef group didn't show significant differences in their protein contents. Hence, a further amino acid analysis was planned to examine the amino acid composition in some example products. Four popular beef products (burgers, mince, meatballs, and pastrami) and their PB beef equivalents were purchased from the supermarket Tesco (a supermarket that has the highest market share in the UK) in February 2022 and sampled on the same day, as detailed in the Supplementary Materials. All the beef products contain at least 86–100% beef. For the PB products, PB burgers contain textured soy and wheat protein; PB mince contains soy protein concentrate and isolate; PB meatballs contain pea protein; and the PB pastrami contains wheat gluten and chickpea flour as their main sources of protein.

Amino acid contents in these PB and beef products were determined using either acid, alkaline, and performic acid hydrolysis as described by Natalia Perez-Moral et al. (Perez-Moral, Saha, Pinto, Bajka, & Edwards, 2023), followed by LC-MS/MS analysis. A schematic description of sample preparation and analysis can be seen in Fig. S1 in the Supplementary Materials, together with the detailed descriptions of the experimental procedures.

2.3. Statistical analysis

The normality of the data was determined by the Shapiro-Wilk test, the Kolmogorov-Smirnov test and QQ plots in each food group for PB and AB products separately. For food groups that were not normally distributed, the Mann-Whitney test was used to compare the nutrient differences (energy, fat, saturated fat, carbohydrates, sugars, fibre, protein, and salt) between PB and AB products. For food groups that are normally distributed, an independent sample *t*-test with Welch's correction was used due to the different sample sizes for PB and AB products. For the amino acid analysis, three biological replicates and triplicate injections of each food sample (four beef and four PB beef alternatives) were carried out, and all data points from LC-MS were averaged +/− the standard deviation (SD) for each food sample. Similar to the nutritional analysis, the data was assessed for normal distribution using a Shapiro-Wilks test. For normally distributed data, an independent sample *t*-test was conducted, and where data failed to show normal distribution, a Mann-Whitney *U* test was conducted to identify whether there was a significant difference between the amino acids contained in beef products and their PB equivalents.

Statistical analysis was performed using SPSS and GraphPad Prism 9. The Nutri-Scores were computed by inputting the nutritional information from products into a calculator developed in R-Studio®.

3. Results

3.1. Back of pack nutrient analysis

According to the normality test (Fig. S2 and Table S2), cheese and fish groups were not normally distributed and were analysed with the Mann-Whitney U test. The rest of the food groups were analysed with an independent sample t-test with Welch's correction. Fig. 1 shows that all seven categories had significantly higher fibre content among the PB products compared to the AB products. All categories except beef ($P = 0.115$) and ready meals ($P = 0.593$) had significantly higher protein content in AB than PB. For salt comparisons, all categories except the sausage group had a higher mean salt content in PB products. However, the differences in the cheese ($P = 0.100$) and chicken ($P = 0.153$) groups were not significant. Compared to the recommended 6 g of salt intake per day in the UK (Recommendations, 2016), the differences in all food groups were minimal (Table 1). The sausage group was the only group that had a significantly higher amount of fat in AB products. Other groups had an insignificantly higher amount of fat in AB products, except fish, chicken, and ready meals, which had an insignificantly higher fat content in PB products. With insignificant differences in other categories, sugar content was significantly higher in PB chicken products ($P < 0.0001$), while significantly lower in PB milk products ($P = 0.001$). In terms of energy content, all categories showed no significant difference between PB and AB products. The complete list of *P* values for nutrient comparisons in each food group can be found in Table 1. AB cheeses had a significantly lower amount of carbohydrates (19.7 g, $P < 0.0001$) and a higher amount of protein (18.9 g, $P < 0.0001$) compared to AB cheeses. The largest difference in fibre between AB and PB products was found in the beef group, where PB products have 4.3 g more fibre ($P < 0.0001$) than AB products on average. The largest difference in fat and saturated fat was found in the sausage group, with an average of 7.1 g more fat ($P = 0.043$) and 2.9 g more saturated fat ($P = 0.039$) in AB sausage products.

3.2. Nutri-Score

The Nutri-Score distributions of AB ($n = 70$) and PB products ($n = 958$) are shown in Fig. 2. All the AB cheese products had Nutri-Scores at the lower end, either E or D, while around 8% of the PB cheeses were scored as C, representing a better nutrient composition in some PB cheeses. However, in the beef, sausage, and chicken groups, although the PB categories have more products with high scores (A or B), they also include a small percentage of D and even E (in the sausage group) that the AB counterparts didn't have, which represented large variations in the nutritional quality in those food groups. In the rest of the food groups, including the milk, ready meals, and fish groups, their PB categories have higher percentages of products with lower scores than their AB counterparts.

3.3. Nutrient supplementations

Fig. 3 shows the scope of certain nutrients supplemented in PB products in each food group. Only food groups containing at least one product being supplemented were included, which results in 1485 products from 11 food groups. Among included products, the 'milk & cream' group had the highest number of products being supplemented, followed by 'ready meals', 'yoghurts', 'other drinks'. In general, 'meat', 'snacks', 'ice cream', and 'sauces' were less likely to be supplemented, comparing to either all included products or within their own respective groups. A detailed breakdown of the numbers and percentages of products being supplemented in each food group can be found in Table S4. Across all food groups, 15% of all plant-based products had been supplemented with vitamin B12, making it the most supplemented nutrient compared to other nutrients, followed by calcium, vitamin D and iron. Other vitamin Bs (excluding vitamin B12 and B2), vitamin A, vitamin C and other vitamins (pantothenic acid, biotin, and vitamin K) were the least commonly supplemented nutrients across all food groups.

Table 2 shows the average amount of nutrients supplemented in different food groups, along with the UK Recommended Nutrient Intakes (RNIs) of each nutrient for the average population (Recommendations, 2016). The majority of the food groups had lower average nutrient supplementations compared to the RNIs, except for vitamin B12 in some food groups, iron and vitamin C in 'other drinks', and vitamin A in 'jams & spreads'. All food groups included in the study had products supplemented with vitamin B12. 'Milk & cream' and 'yoghurt' group had the least average amount of vitamin B12 supplemented, whereas 'bacon & sausages' and 'jams & spreads' had the highest average. However, the high averages do not represent the majority of the products in those groups, as they were mostly contributed by a few products that had a larger amount of vitamin B12 supplementation. Protein shakes from the 'other drinks' group were the main contributors to the high average amounts of iron and vitamin C.

3.4. Amino acid analysis

To evaluate the protein quality of PB against AB products we selected four representative products from burgers, mince, meatballs, and pastrami categories and quantified their individual AA content analytically. In Table 3, the content of most of the amino acids was significantly higher in all beef products except beef mince. For essential amino

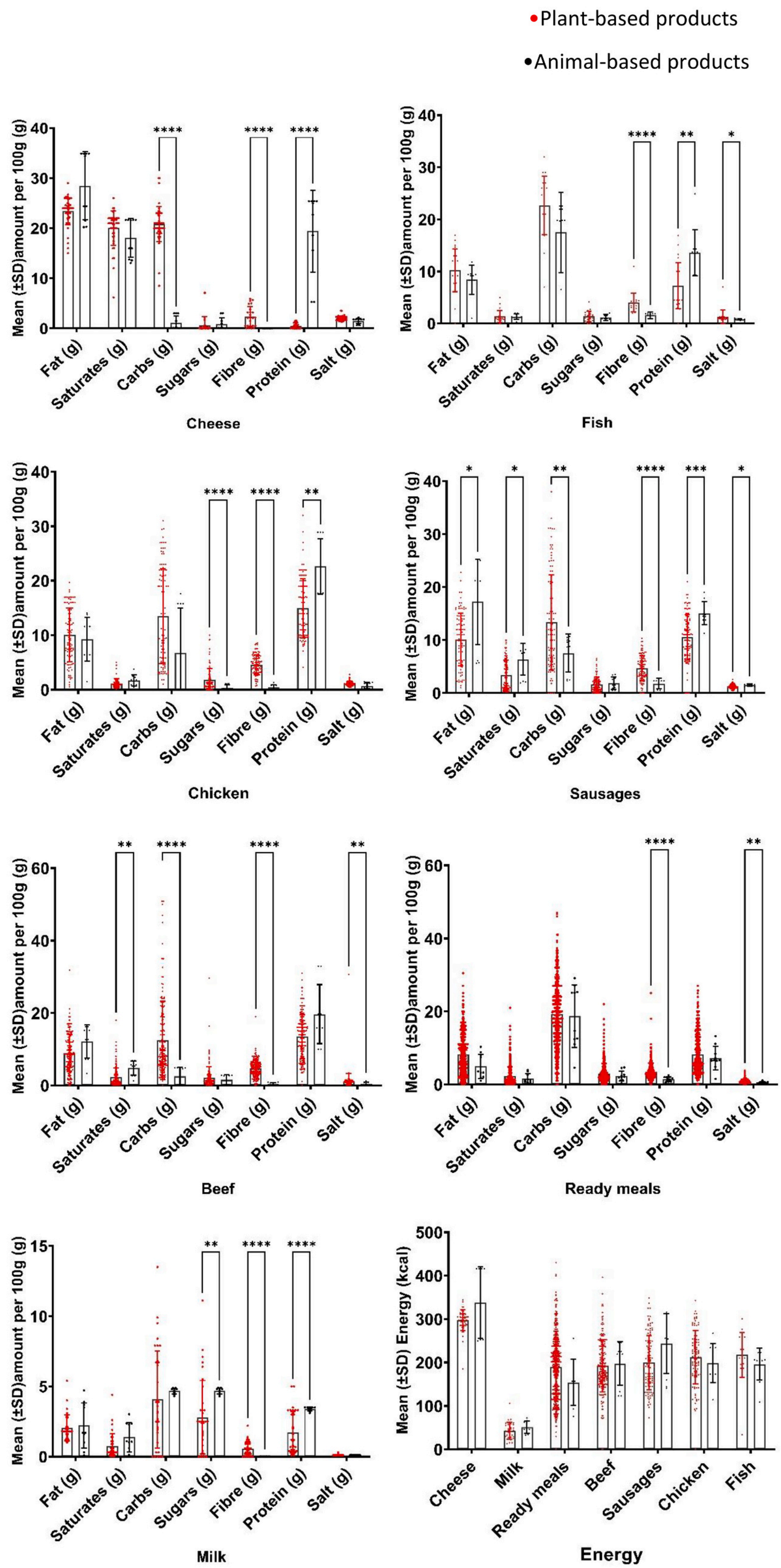

Fig. 1. Comparisons of the mean (±SD) back of pack nutrient contents between plant-based (PB) and animal-based (AB) products in each food group. Cheese and fish groups were not normally distributed and were analysed with the Mann-Whitney *U* test. The rest of the food groups were analysed with an independent sample *t*-test with Welch's correction. Statistical significance is indicated as follows: *$P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$, **** $P \leq 0.0001$.

Table 1
The mean differences and *P* values of the back of pack nutrient contents between AB and PB products in each food group (positive indicates higher in AB whilst negative indicates higher in PB). Statistical significance is indicated as follows: $^*P \le 0.05$, $^{**}P \le 0.01$, $^{***}P \le 0.001$, $^{****}P \le 0.0001$.

Food Groups		Fat (g)	Saturates (g)	Carbs (g)	Sugars (g)	Fibre (g)	Protein (g)	Salt (g)
Cheese	P value	0.217	0.217	<0.0001****	0.217	<0.0001****	<0.0001****	0.100
	Mean Diff.	5.1	−2.0	−19.7	0.3	−2.3	18.9	−0.5
Fish	P value	0.557	0.557	0.206	0.818	<0.0001****	0.004**	0.018*
	Mean Diff.	−1.8	−0.1	−5.2	−0.2	−2.4	6.3	−0.5
Milk	P value	0.935	0.337	0.685	0.0011**	<0.0001****	<0.0001****	0.935
	Mean Diff.	0.2	0.7	0.6	1.9	−0.6	1.7	0.0
Beef	P value	0.120	0.010**	<0.0001****	0.200	<0.0001****	0.115	0.006**
	Mean Diff.	3.1	2.5	−9.9	−0.6	−4.3	6.2	−0.7
Chicken	P value	0.574	0.246	0.116	<0.0001****	<0.0001****	0.004**	0.153
	Mean Diff.	−0.8	0.5	−6.8	−1.5	−4.2	7.7	−0.4
Sausage	P value	0.043*	0.039*	0.003**	0.621	<0.0001****	0.000199***	0.034*
	Mean Diff.	7.1	2.9	−5.8	0.2	−2.9	4.5	0.2
Ready meals	P value	0.061	0.443	0.834	0.443	<0.0001****	0.593	0.002**
	Mean Diff.	−3.3	−0.7	−0.6	−0.7	−2.0	−1.0	−0.5

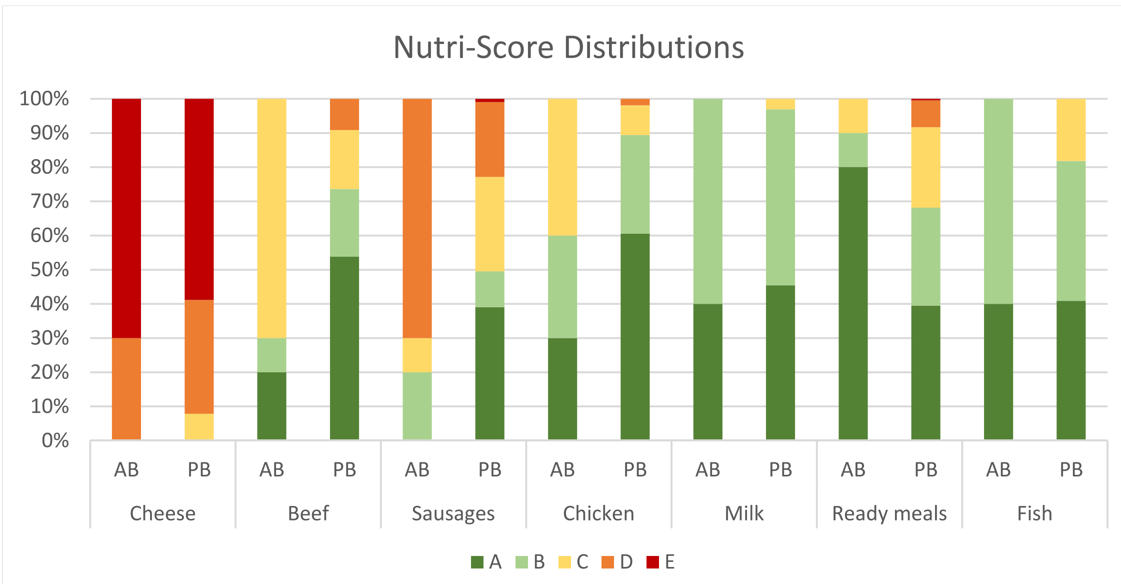

Fig. 2. The Nutri-Score distributions of AB and PB products for each food category. 'A' representing the highest nutritional value and 'E' representing the lowest nutritional value.

acids, all beef products had higher contents (both significantly and non-significantly) of histidine, methionine, lysine and threonine. For non-essential amino acids, all beef products had higher contents of alanine and glycine. In all products except meatballs, the PB products had higher amount of phenylalanine, GLX, proline, and serine. Table S5 lists the detailed average amino acid content for each product.

To identify the quantity of amino acids in each sample relative to the amount of protein in the individual products, the percentage of total protein was individually calculated using the sample wet weight (detailed in Table S6). The protein contents of PB pastrami and mince were slightly higher than those of beef versions, whereas PB meatballs only contain 60% of the protein content of beef meatballs. Despite the fact that the protein contents in some PB products were higher, when plotted as a percentage of total protein in Fig. 4, it was evident that all the beef products contained a higher percentage of EAAs compared to the PB products. Beef pastrami contained the highest percentage of EAAs, followed by beef meatballs, beef burgers, and beef mince. On the contrary, PB pastrami had the lowest percentage of EAAs, showing the biggest gap in EAA% between the AB and PB versions. Mince and meatballs had the smallest gap between the AB and PB versions.

4. Discussion

The PB diet has gained popularity in the western world with its claim of a dual-edged impact on alleviating the burden of compromised health conditions while also addressing the environmental consequences of food production. With the growth of novel PB products, this study investigated the nutritional profile of these items from different angles, particularly within the context of the UK market. Briefly, PB products from all food groups consistently exhibit higher fibre contents and lower protein contents compared to their AB counterparts. High salt contents were detected in some but not all products. As for general nutritional quality, PB products are more likely to have higher Nutri-Scores compared to AB counterparts, but they also come with larger score variations within each food group. The nutrient fortifications were primarily focused on dairy and ready meals. The most frequently supplemented nutrient is vitamin B12; however, it was only found in 15% of all products. Through the amino acid analysis of four pairs of beef and beef alternatives, it was found that all beef products, except beef mince, have significantly higher contents of nearly all EAAs. This trend has led to a higher proportion of EAAs in comparison to total protein contents in all beef products compared to their PB alternatives.

One of the advantages of PB products is their high fibre content. This

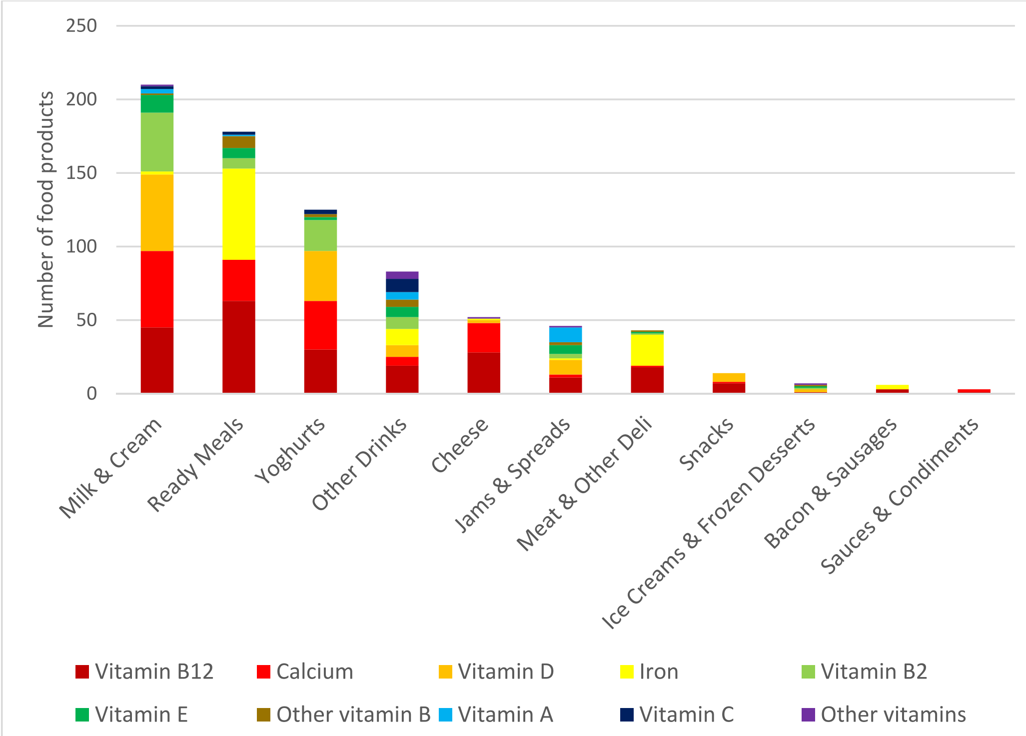

Fig. 3. The number of PB products (total number of products = 1485) in each food group that has specific nutrient supplementations.

Table 2
The average amount of nutrients supplemented, stratified by food groups.

Food Groups		Average amount of nutrients supplemented							
		Vitamin B12 (μg/100 g)	Calcium (mg/ 100 g)	Vitamin D (μg/ 100 g)	Iron (mg/ 100 g)	Vitamin B2 (mg/100 g)	Vitamin E (mg/ 100 g)	Vitamin A (μg/ 100 g)	Vitamin C (mg/ 100 g)
Milk & Cream		0.4	142	0.8	9.1	0.2	3	219	37
Ready Meals		0.9	346		3.1			135	18
Yoghurts		0.4	122	0.7		0.2	1		4
Other Drinks		1.9	312	0.9	17.6	1.0	14	741	128
Cheese		2.2	294	1.2	2.1				
Jams & Spreads		2.8	135	6.8	2.1		29	820	
Meat & Other Deli		0.6	120		4.0	0.2	3		
Snacks		2.1	282	3.6					
Ice Creams & Frozen Desserts		0.8		2.4		0.5	4		
Bacon & Sausages		2.9			5.7				
Sauces & Condiments		1.5	200						
RNIs (adults aged 19 to 64)	Male	1.5 μg/d	700 mg/d	10 μg/d	8.7 mg/d	1.3 mg/d	–	700 μg/d	40 mg/d
	Female	1.5 μg/d	700 mg/d	10 μg/d	14.8 mg/d	1.1 mg/d	–	600 μg/d	40 mg/d

study demonstrated that across all seven food categories, PB products exhibited significantly higher fibre content compared to AB products. This trend has been observed in numerous studies conducted in different countries (Boukid, 2021; Bryngelsson et al., 2022; Clegg, Ribes, Reynolds, Kliem, & Stergiadis, 2021; Cole, Goeler-Slough, Cox, & Nolden, 2022; L. Harnack et al., 2021; Katidi, Xypolitaki, Vlassopoulos, & Kapsokefalou, 2023; Tonheim, Austad, Torheim, & Henjum, 2022). Given that plants are known to naturally contain fibre, it logically follows that products made with mainly plant sources would inherently have greater fibre content, except for those made with primarily isolated plant proteins. Sometimes fibre can be added as a functional ingredient as well (McClements & McClements, 2023). Furthermore, the substitution of AB products with PB alternatives has been shown to promote overall fibre intake in dietary modelling studies (Salomé et al., 2021; Seves, Verkaik-Kloosterman, Biesbroek, & Temme, 2017). Insufficient fibre intake is a prevalent issue in Western countries (van der Weele, Feindt, Jan van der Goot, van Mierlo, & van Boekel, 2019). In the UK specifically, the average daily intake of fibre is 19.7 g/d for adults 19–64 years old measured from 2016 to 2019, considerably lower than the recommended 30 g/day (Bates et al., 2020). Low fibre intake is closely linked to the development of chronic conditions such as cardiovascular disease, type 2 diabetes, and cancer (Toribio-Mateas, Bester, & Klimenko, 2021). This augmented fibre content provided by PB products has the potential to contribute towards aligning the population's fibre intake more closely with established recommendations.

Nevertheless, an improved fibre intake can also be achieved through the consumption of traditional PB foods like tofu and tempeh, and even more straightforwardly, from minimally processed grains, nuts, seeds, vegetables, and fruits. Robust evidence supports their associations with increased micronutrient intakes and efficacy in improving health and reducing the risk of chronic diseases (Tso & Forde, 2021), and they are notably more affordable than the novel PB products (Blanco-Gutiérrez, Varela-Ortega, & Manners, 2020). While these foods might not fully substitute meat within conventional meat-centred diets (Beardsworth &

Table 3
The mean amino acid differences (in grams) and *P* values in 100 g beef and PB beef products. Values are calculated from the wet weight of the product.

	Amino acid	Difference in burgers (AB-PB)	Difference in mince (AB-PB)	Difference in meatball (AB-PB)	Difference in pastrami (AB-PB)
Essential amino acids	Tryptophan	0.02*	−0.10**	0.13***	0.12***
	Phenylalanine	−0.13***	−0.39***	0.03	−0.71***
	Histidine	0.25***	0.04	0.36***	0.16*
	Methionine	0.17***	0.16**	0.29***	0.04
	Lysine	0.89***	0.12	0.34**	2.96***
	Leucine	0.01***	−0.01**	0.02***	−0.01**
	Isoleucine	0.06*	−0.04	0.22***	−0.42***
	Threonine	0.24***	0.02	0.32***	0.25**
	Valine	0.15***	−0.13***	0.27***	−0.16
Non-essential amino acids	Tyrosine	0.04*	0.12	−0.04	0.01
	Arginine	0.11***	−0.29***	0.02	0.20
	GLX	−0.96***	−1.02***	0.45**	−7.52***
	Proline	−0.40***	−0.21***	0.23**	−3.41***
	Serine	−0.04*	−0.39***	0.07	−0.67***
	Alanine	0.48***	0.32***	0.46***	0.20*
	Cystine	0.16	−0.55***	0.02	−0.16
	Glycine	0.02	0.04**	0.14**	0.17***
	ASX	0.20***	−0.76***	0.08	0.95***

Note: GLX is glutamic acid + glutamine. ASX is aspartic acid + asparagine. P values were calculated using an independent sample T-test. Negative values represent higher AA contents in PB products. Statistical significance is indicated as follows: *$P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$, **** $P \leq 0.0001$.

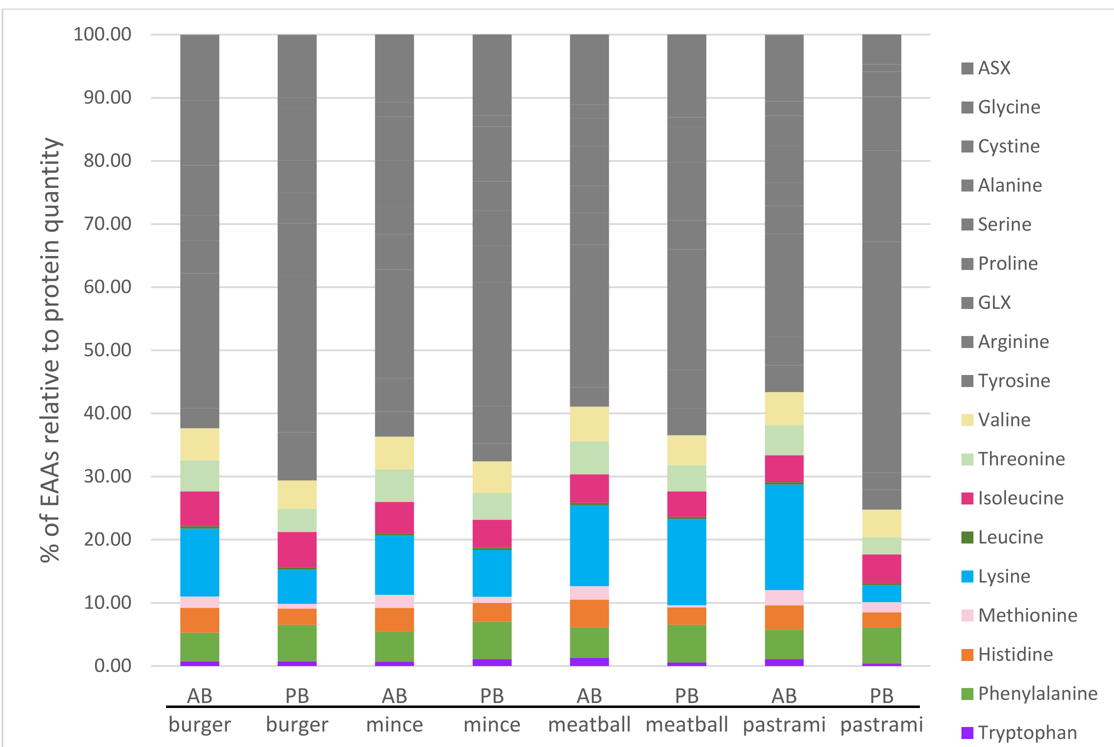

Fig. 4. The amino acids shown as the percentage of total protein in AB and PB equivalent products. EAAs are in colour and the non-essential amino acids are grey. The percentage of EAAs: AB burger (37.64%), PB burger (29.38%), AB mince (36.30%), PB mince (32.42%), AB meatball (41.06%), PB meatball (35.98%), AB pastrami (43.39%), PB pastrami (24.78%).

Bryman, 2004), their consumption needs improving for western populations (Willett et al., 2019). The original intent behind the development of novel PB products was to mimic and replace meat, which led to the addition of nutrients like sugar, fat, and salt (Aydar, Tutuncu, & Ozcelik, 2020; McClements & McClements, 2023; Tachie, Nwachukwu, & Aryee, 2023; Tso & Forde, 2021), along with additives and colourings (Giacalone, Clausen, & Jaeger, 2022; Hartmann, Furtwaengler, & Siegrist, 2022) to enhance the organoleptic properties of these products or to replicate the appearance and texture of meat (Nolden & Forde, 2023). Additionally, they typically contain lower micronutrient contents in comparison to traditional plant-based foods, largely attributable to food processing (Tso & Forde, 2021). Nonetheless, there are contrasting findings concerning salt and particularly sugar (Nolden & Forde, 2023). In this study, the average sugar content was significantly lower in PB milk products ($P = 0.001$) but showed a large variation within the group compared to AB milks. This broad variation is also observable in chicken, beef, sausages, and ready meals. In terms of salt, across all food groups except the sausage group, PB products generally exhibit a higher average salt content. Yet, the variability in salt content is not as pronounced as that of sugar, and the disparity between PB and AB doesn't markedly exceed the daily allowance of 6 g. Hence, the emphasis on reducing salt intake should be on decreasing the consumption of foods that are generally high in salt, rather than specifically targeting plant-based foods. Consequently, it's premature to assume that all PB products have higher levels of health-sensitive nutrients. Given that food industries consistently reformulate or introduce new products, it is imperative to evaluate them on a case-by-case basis.

Regarding PB products that exhibit comparable nutrient profiles to AB counterparts, they cannot be readily deemed healthy. This study did not specifically delve into the ingredient lists of these products, yet findings from other studies indicate that novel PB products often have longer ingredient lists containing additives like colouring, flavouring, binding agents, preservatives, emulsifiers, and more (Giacalone, Clausen, & Jaeger, 2022; Hartmann et al., 2022; Tachie et al., 2023). While the precise dose-response associations between prolonged consumption of food additives and health outcomes remain uncertain, it's important to note that these novel PB products often fall within the classification of ultra-processed foods, which have been linked to adverse long-term health effects (23). Thus, when evaluating the health impact of processed foods, the role of additives and their interactions with other food components should not be dismissed (24). In addition, the effects of processing itself remain unclear.

Protein is another key nutrient that was found to be significantly lower in most PB products, consistent with findings in other studies (Cole et al., 2022; Gorissen et al., 2018; Nolden & Forde, 2023). Even within the beef group, where the difference wasn't statistically significant, a further amino acid analysis revealed that the content of essential amino acids was notably higher in all beef products. The PB burgers and pastrami included in this study were made with both wheat and legume protein, which could ideally compensate their limiting EAAs, lysine and methionine content, respectively (Boye, Zare, & Pletch, 2010; Mariotti & Gardner, 2019). However, the contents of histidine, methionine, lysine and threonine were consistently lower in all PB products; similar limiting EAAs in PB products were also found in previous studies (De Marchi, Costa, Pozza, Goi, & Manuelian, 2021; Gorissen et al., 2018; Mathai, Liu, & Stein, 2017). In comparison to the recommended AA intake published by WHO (Protein and amino acid requirements in human nutrition: report of a joint FAO/WHO/UNU expert consultation, 2007), replacing these AB products with PB alternatives would lead to a higher chance of individuals failing to meet the recommended intakes of certain AAs. Sustained inadequate intake of a specific amino acid can potentially lead to oxidation of the remaining amino acids, which further decreases the bioavailability of the digested amino acids (Domic et al., 2022; Moehn, Bertolo, Pencharz, & Ball, 2005). The AA discrepancies in AB and PB mince were comparatively less pronounced, presumably because it was made with soya concentrate and isolates, which are deemed to closely resemble animal protein in terms of protein quality (Gorissen et al., 2018; Schaafsma, 2000; Vanga & Raghavan, 2018). However, it shares the same limiting AAs as other PB products, likely due to the processing of protein extractions or interactions with other components within the food (Meade, Reid, & Gerrard, 2005; Rutherfurd & Moughan, 2012; Schutyser, Pelgrom, Van der Goot, & Boom, 2015; Singh, Gamlath, & Wakeling, 2007). This highlights the importance of obtaining and maintaining, at the national level, accurate AA composition data for a variety of ingredients, which should inform new PB product development.

The composition of AAs is one of the key criteria for assessing protein quality. However, evaluating protein quality requires consideration of other factors, such as the presence of antinutritional components like phytate, tannins, and fibre in most plant foods. These components can notably decrease the accessibility and digestibility of proteins (Scholz-Ahrens, Ahrens, & Barth, 2020; Verduci et al., 2019). While this study lacked the necessary resources and data to estimate the content of antinutritional factors in the products, it's clear that the combination of lower protein content and the potential hindrance of protein absorption further reduces the pool of amino acids available for utilization by the human body (Forde & Bolhuis, 2022). Nevertheless, protein extraction and extrusion techniques could potentially improve the digestibility of protein from plant-based products, partially by reducing the content of antinutritional factors (Mayer Labba, Steinhausen, Almius, Bach Knudsen, & Sandberg, 2022; Pinckaers, Trommelen, Snijders, & van Loon, 2021; Singh et al., 2007). When discussing protein adequacy, it's essential to take into account the population's status. The average protein intake within Western populations exceeds recommended levels (Mayer Labba et al., 2022; van der Weele et al., 2019). Thus, within the general population, a reduction in protein coupled with an enhancement in fibre could help achieve a balanced intake of these two nutrients; the additional consumption of antinutritional components is shown to be beneficial to health as well (Toribio-Mateas et al., 2021; van Vliet et al., 2021). However, this dietary transition might fall short of providing sufficient protein for population groups that have higher protein requirements, such as older adults, people who are pregnant or breastfeeding, or people with certain medical conditions (Clegg et al., 2021; Domic et al., 2022).

To comprehensively assess the nutritional quality of a product, it is advisable to apply a nutrition profiling system that takes into consideration multiple nutrient contents rather than evaluating each nutrient individually. The Nutri-Score algorithm serves as an example and is extensively used on the front-of-pack of food items in various European countries. This system integrates considerations of both nutrients and the consumption of beneficial food groups, including fruits, vegetables, pulses, nuts, and olive/rapeseed/walnut oil (Hercberg, Touvier, & Salas-Salvado, 2021). It ranks the nutritional quality with a single score from A to E for each product, simplifying categorization and comparisons across foods. In this study, PB products exhibited a broad range of scores in all food groups, in contrast to the more consistent scores observed in animal products (Katidi et al., 2023). This variance can be attributed to the diverse compositions and additives found in PB products, compared to the relatively less heterogeneous nature of AB products (Ma et al., 2022). The contributions of beneficial food groups weren't incorporated in calculating the Nutri-Score, given that the ingredient compositions of most products don't provide enough information to make accurate assumptions about their proportions. However, it's assumed that the Nutri-Score of PB products would likely improve further overall once these aspects are factored in. This observation aligns with the earlier nutritional comparisons and underscores that it's inadvisable to make a blanket judgment that all PB products are inherently unhealthy or healthy. Rather, a more prudent approach involves individualized assessment of their overall nutritional quality, additives, inclusion of antinutritional factors, and the existence of other key micronutrients (Bohrer, 2019).

Neither nutritional labels nor nutritional profiling systems account for most minerals and vitamins (Flint et al., 2023). Special consideration is warranted when replacing all animal products with novel PB alternatives (Rust et al., 2020). It has been observed that such products tend to offer lower amounts of vital elements like calcium, iron, iodine, selenium, vitamin B2, and vitamin B12 (Aimutis, 2022; Bryngelsson et al., 2022; Clarys et al., 2014; L. Harnack et al., 2021). Especially nutrients like vitamin B12, which are exclusive to animal-derived foods. Prolonged deficiencies in one or more of these nutrients without regular supplementation can give rise to serious health consequences (Gilsing et al., 2010). Fortifying nutrients in food products has proven effective in maintaining recommended vitamin B12 intake levels without the need for supplements (Turner-McGrievy et al., 2008). Within this study, a substantial majority of PB products lacked nutrient fortification, aligning with findings from previous studies conducted in various countries (Curtain & Grafenauer, 2019; D'Andrea et al., 2023; L. J. Harnack, Reese, & Johnson, 2022; Walther et al., 2022). Vitamin B12 was supplemented in just 15% of all products, and approximately half of PB dairy products. Another nutrient of concern is iodine, with only 12 out of 1485 products containing iodine supplementation, a limitation also evident in Clegg et al., 2021 (Clegg et al., 2021). Dairy products constitute the primary source of vitamin B12 and iodine intake for all age groups in the UK (Alzahrani, Ebel, Norton, Raab, & Feldmann, 2023; Matte, Britten, & Girard, 2014). Particularly noteworthy is the absence of a formal iodine fortification program in the UK. People predominantly obtain iodine from dairy products due to the practice of adding iodine to cattle feed, which elevates iodine levels in milk. Without dairy consumption and the inclusion of iodine-fortified PB products, there's a significant risk of iodine deficiency (Dineva, Rayman, & Bath, 2021; Woodside & Mullan, 2021). Additional concerns for nutrient supplementation include the unstable nature of some nutrients within the plant food matrix (Walther et al., 2022), the impact of extensive food processing on the bioavailability of sensitive nutrients (Aguilera, 2019). Plus, antinutritional components present in plants can interfere with the subsequent digestion and absorption of nutrients (Rousseau, Kyomugasho, Celus, Hendrickx, & Grauwet, 2020; Walther et al., 2022). Hence, similar to the case with protein, the actual utilization of nutrients by the human body including that of fortified nutrients is subject to high variability, often differing from what is stated on the nutritional label (Forde & Bolhuis, 2022).

The current study has certain limitations that need acknowledgment. The data presented is a snapshot in time, reflective of the UK market, particularly the market for novel PB products, which is constantly updated (Guess et al., 2023). Employing longitudinal data collection and analysis would offer a more accurate representation of market trends. Unlike observational human studies, the analysis in this study could not directly capture real food consumption habits, making it challenging to draw conclusions regarding the extent to which individuals integrate these products into their diets. This is important because partial replacement of animal products would yield different nutrient and health outcomes compared to complete replacements (Derbyshire, 2017). Due to the limited data available, our assessment was confined to the nutrients explicitly mentioned on product packaging, excluding other vital micronutrients and plant components that play a pivotal role in determining nutritional quality. Matching each PB product with a perfect AB alternative proved impractical due to the lack of industry standards for compositions and the extensive variation in ingredients and food processing methods across different PB manufacturers (Tyndall, Maloney, Cole, Hazell, & Augustin, 2022). Consequently, more options for PB products were aligned with fewer, more generic AB counterparts. This study does leverage a substantial portion of the available product information, filling gaps in existing research by offering an overarching perspective on nutrient compositions, quality, supplementation, and by delving into the amino acid profiles of PB products. It serves as a guide for future efforts within the food industry, indicating the type of data that would facilitate the evaluation of product quality, including ingredient proportions and the presence of limited micronutrients in PB foods, among others.

Based on the analysis, it's evident that the current information available on food labels falls short of equipping consumers to make well-informed choices (Nolden & Forde, 2023; B. Ridoutt, 2023). The study did not evaluate the correspondence between health claims and the actual nutrient contents. Guess et al. (2023) discovered that these claims frequently do not align with the real nutrient composition (Guess et al., 2023). These novel products are generally more expensive and convey a perception of being superior for both health and the environment (B. Ridoutt, 2023; Sadler et al., 2022). While PB products do exhibit a more favourable environmental impact compared to animal products (Boukid, 2021; Bryant, 2022; Carlsson Kanyama, Hedin, & Katzeff, 2021), the complexity of processed foods, involving numerous stages before reaching the final product, requires a standardized and comprehensive evaluation of the impact at each step (B. Ridoutt, 2023; Rosi et al., 2017). Unfortunately, the methods to evaluate environmental impact are currently quite diverse, making it challenging to apply one specific set of indicators to a wide range of food products (Andreani et al., 2023). Furthermore, studies have highlighted that a diet that is beneficial for the environment may not necessarily be good for health, and vice versa (González-García, Esteve-Llorens, Moreira, & Feijoo, 2018; Heerschop, Kanellopoulos, Biesbroek, & van 't Veer, P., 2023; B. G. Ridoutt, Baird, & Hendrie, 2021). This complexity further underscores the need for individuals to be well-informed about their specific nutritional needs, which is rather difficult without consulting a healthcare professional, e. g., a dietitian. Therefore, it is currently challenging to achieve a balance that considers both the environmental and health impacts of one's diet and lifestyle. Innovations in food labelling that address both aspects have the potential to contribute to achieving this goal.

This study employed a large dataset containing product information from a significant portion of the food products available in the UK market. It encouraged efforts to utilize such a dataset to disseminate scientific findings related to food quality that can shape our food system and enhance population health. Future investigations can extend to other dimensions of the collected data, such as ingredients and health claims, leveraging machine learning and data mining technologies to uncover correlations between these attributes and product nutritional quality. Estimations on nutrient digestibility and bioavailability can also be done potentially when ingredient data are linked to relevant nutritional and antinutrient compositions (Hunt, 2003). This approach holds the potential to catalyse transformative changes in our food systems by emphasizing holistic nutrient quality, empowering consumers (Cutroneo et al., 2022) and promoting improved product formulations. The continuous collection and analysis of data can deliver the information needed for monitoring the food supply chain and understanding dynamics of the food system (Wickramasinghe et al., 2021). Moreover, it enables regulators and policymakers to swiftly adapt and refine food policies (B. G. Ridoutt, Hendrie, & Noakes, 2017).

5. Conclusions

Through the analysis of the nutritional information of the majority of the PB products within the UK market, it was evident that, in general, PB products have a higher amount of fibre, a lower amount of protein, and a varied nutritional profile compared to their AB counterparts. However, the determination of their overall healthfulness is not straightforward and hinges on several factors. These include ingredient compositions, additives, nutrient fortifications, personal nutrient requirements, and the extent to which these products are integrated into individual diets. In making decisions about their health merits, it's essential to weigh these considerations on a case-by-case basis. Collaborative efforts and sharing of data involving stakeholders, food manufacturers, and policymakers are pivotal to empowering consumers to make well-informed choices, standardize methods for assessing environmental impact, enhancing product transparency, and improving our food system and supply chain.

CRediT authorship contribution statement

Liangzi Zhang: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Ellie Langlois:** Writing – original draft, Visualization, Resources, Investigation, Formal analysis. **Katie Williams:** Writing – original draft, Visualization, Resources, Investigation, Formal analysis. **Noemi Tejera:** Writing – review & editing, Supervision, Methodology, Investigation. **Maja Omieljaniuk:** Software. **Paul Finglas:** Writing – review & editing, Supervision, Funding acquisition. **Maria H. Traka:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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.

Data availability

Data will be made available on request.

Acknowledgement

This work was supported by the UKRI Biotechnology and Biological Sciences Research Council (BBSRC) Core Capability Grant BB/CCG2260/1 and its constituent project BBS/E/QU/23NB0006 (Food & Nutrition National Bioscience Research Infrastructure).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2024.139059.

References

Aguilera, J. M. (2019). The food matrix: Implications in processing, nutrition and health. *Critical Reviews in Food Science and Nutrition, 59*(22), 3612–3629.

Aimutis, W. R. (2022). Plant-based proteins: The good, bad, and ugly. *Annual Review of Food Science and Technology, 13*, 1–17.

Alae-Carew, C., Green, R., Stewart, C., Cook, B., Dangour, A. D., & Scheelbeek, P. F. D. (2022). The role of plant-based alternative foods in sustainable and healthy food systems: Consumption trends in the UK. *Science of the Total Environment, 807*, Article 151041. https://doi.org/10.1016/j.scitotenv.2021.151041

Aleksandrowicz, L., Green, R., Joy, E. J., Smith, P., & Haines, A. (2016). The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: A systematic review. *PLoS One, 11*(11), Article e0165797. https://doi.org/10.1371/journal.pone.0165797

Alzahrani, A., Ebel, R., Norton, G., Raab, A., & Feldmann, J. (2023). Iodine in plant-based dairy products is not sufficient in the UK: A market survey. *Journal of Trace Elements in Medicine and Biology, 79*, Article 127218. https://doi.org/10.1016/j.jtemb.2023.127218

Andreani, G., Sogari, G., Marti, A., Froldi, F., Dagevos, H., & Martini, D. (2023). Plant-based meat alternatives: Technological, nutritional, environmental, market, and social challenges and opportunities. *Nutrients, 15*(2), 452. https://www.mdpi.com/2072-6643/15/2/452.

Aydar, E. F., Tutuncu, S., & Ozcelik, B. (2020). Plant-based milk substitutes: Bioactive compounds, conventional and novel processes, bioavailability studies, and health effects. *Journal of Functional Foods, 70*, Article 103975. https://doi.org/10.1016/j.jff.2020.103975

Bakaloudi, D. R., Halloran, A., Rippin, H. L., Oikonomidou, A. C., Dardavesis, T. I., Williams, J., … Chourdakis, M. (2021). Intake and adequacy of the vegan diet. A systematic review of the evidence. *Clinical Nutrition, 40*(5), 3503–3521. https://doi.org/10.1016/j.clnu.2020.11.035

Bates, B., Collins, D., Jones, K., Page, P., Roberts, C., Steer, T., & Swan, G. (2020). *NDNS: Results from years 9 to 11 (2016 to 2017 and 2018 to 2019)*.

Beardsworth, A., & Bryman, A. (2004). Meat consumption and meat avoidance among young people: An 11-year longitudinal study. *British Food Journal, 106*(4), 313–327.

van der Bend, D. L. M., van Eijsden, M., van Roost, M. H. I., de Graaf, K., & Roodenburg, A. J. C. (2022). The Nutri-score algorithm: Evaluation of its validation process. *Frontiers in Nutrition, 9*, Article 974003. https://doi.org/10.3389/fnut.2022.974003

Blanco-Gutiérrez, I., Varela-Ortega, C., & Manners, R. (2020). Evaluating animal-based foods and plant-based alternatives using multi-criteria and SWOT analyses. *International Journal of Environmental Research and Public Health, 17*(21), 7969. https://www.mdpi.com/1660-4601/17/21/7969.

Bohrer, B. M. (2019). An investigation of the formulation and nutritional composition of modern meat analogue products. *Food Science and Human Wellness, 8*(4), 320–329. https://doi.org/10.1016/j.fshw.2019.11.006

Boukid, F. (2021). Plant-based meat analogues: From niche to mainstream. *European Food Research and Technology, 247*(2), 297–308.

Boye, J., Zare, F., & Pletch, A. (2010). Pulse proteins: Processing, characterization, functional properties and applications in food and feed. *Food Research International, 43*(2), 414–431.

Brooker, P. G., Hendrie, G. A., Anastasiou, K., & Colgrave, M. L. (2022). The range and nutrient profile of alternative protein products sold in Australian supermarkets between 2014 and 2021. *International Journal of Food Sciences and Nutrition, 73*(8), 1067–1079. https://doi.org/10.1080/09637486.2022.2137786

Bryant, C. J. (2022). Plant-based animal product alternatives are healthier and more environmentally sustainable than animal products. *Future Foods, 6*, Article 100174. https://doi.org/10.1016/j.fufo.2022.100174

Bryngelsson, S., Moshtaghian, H., Bianchi, M., & Hallström, E. (2022). Nutritional assessment of plant-based meat analogues on the Swedish market. *International Journal of Food Sciences and Nutrition, 73*(7), 889–901.

Carlsson Kanyama, A., Hedin, B., & Katzeff, C. (2021). Differences in environmental impact between plant-based alternatives to dairy and dairy products: A systematic literature review. *Sustainability, 13*(22), 12599. https://www.mdpi.com/2071-1050/13/22/12599.

Clarys, P., Deliens, T., Huybrechts, I., Deriemaeker, P., Vanaelst, B., De Keyzer, W., … Mullie, P. (2014). Comparison of nutritional quality of the vegan, vegetarian, semi-vegetarian, pesco-vegetarian and omnivorous diet. *Nutrients, 6*(3), 1318–1332. https://doi.org/10.3390/nu6031318

Clegg, M. E., Ribes, A. T., Reynolds, R., Kliem, K., & Stergiadis, S. (2021). A comparative assessment of the nutritional composition of dairy and plant-based dairy alternatives available for sale in the UK and the implications for consumers' dietary intakes. *Food Research International, 148*, Article 110586.

Cole, E., Goeler-Slough, N., Cox, A., & Nolden, A. (2022). Examination of the nutritional composition of alternative beef burgers available in the United States. *International Journal of Food Sciences and Nutrition, 73*(4), 425–432.

Composition of Foods integrated dataset. (2021). PHE (Public Health England). https://www.gov.uk/government/publications/composition-of-foods-integrated-dataset-cofid.

Curtain, F., & Grafenauer, S. (2019). Plant-based meat substitutes in the flexitarian age: An audit of products on supermarket shelves. *Nutrients, 11*(11), 2603.

Cutroneo, S., Angelino, D., Tedeschi, T., Pellegrini, N., Martini, D., Dall'Asta, M., … Paolella, G. (2022). Nutritional quality of meat analogues: Results from the food labelling of italian products (FLIP) project. *Frontiers in Nutrition, 9*, Article 852831.

D'Andrea, A. E., Kinchla, A. J., & Nolden, A. A. (2023). A comparison of the nutritional profile and nutrient density of commercially available plant-based and dairy yogurts in the United States. *Frontiers in Nutrition, 10*. https://doi.org/10.3389/fnut.2023.1195045

De Marchi, M., Costa, A., Pozza, M., Goi, A., & Manuelian, C. L. (2021). Detailed characterization of plant-based burgers. *Scientific Reports, 11*(1), 2049. https://doi.org/10.1038/s41598-021-81684-9

Derbyshire, E. J. (2017). Flexitarian diets and health: A review of the evidence-based literature. *Frontiers in Nutrition, 3*, 55.

Dietary choices of Brits (e.g. vegeterian, flexitarian, meat-eater etc). (2023). London: YouGov PLC.

Dineva, M., Rayman, M., & Bath, S. C. (2021). Iodine status of consumers of milk-alternative drinks v. cows' milk: Data from the UK National Diet and nutrition survey. *British Journal of Nutrition, 126*(1), 28–36.

Domic, J., Grootswagers, P., van Loon, L. J. C., & de Groot, L. (2022). *Perspective: Vegan diets for older adults? A perspective on the potential impact on muscle mass and strength*. Advances in Nutrition. https://doi.org/10.1093/advances/nmac009

European consumer survey on plant-based foods - describing the product landscape and uncovering priorities for product development and improvement. (2020). Berlin: ProVeg International.

Flint, M., Bowles, S., Lynn, A., & Paxman, J. R. (2023). Novel plant-based meat alternatives: Future opportunities and health considerations. *Proceedings of the Nutrition Society*, 1–16. https://doi.org/10.1017/S0029665123000034

Forde, C. G., & Bolhuis, D. (2022). Interrelations between food form, texture, and matrix influence energy intake and metabolic responses. *Current Nutrition Reports, 11*(2), 124–132.

Gehring, J., Touvier, M., Baudry, J., Julia, C., Buscail, C., Srour, B., … Alles, B. (2021). Consumption of ultra-processed foods by Pesco-vegetarians, vegetarians, and vegans: Associations with duration and age at diet initiation. *Journal of Nutrition, 151*(1), 120–131. https://doi.org/10.1093/jn/nxaa196

Giacalone, D., Clausen, M. P., & Jaeger, S. R. (2022). Understanding barriers to consumption of plant-based foods and beverages: Insights from sensory and consumer science. *Current Opinion in Food Science, 48*, 100919.

Gilsing, A. M., Crowe, F. L., Lloyd-Wright, Z., Sanders, T. A., Appleby, P. N., Allen, N. E., & Key, T. J. (2010). Serum concentrations of vitamin B12 and folate in British male omnivores, vegetarians and vegans: Results from a cross-sectional analysis of the EPIC-Oxford cohort study. *European Journal of Clinical Nutrition, 64*(9), 933–939. https://doi.org/10.1038/ejcn.2010.142

González-García, S., Esteve-Llorens, X., Moreira, M. T., & Feijoo, G. (2018). Carbon footprint and nutritional quality of different human dietary choices. *Science of the Total Environment, 644*, 77–94. https://doi.org/10.1016/j.scitotenv.2018.06.339

Gorissen, S. H. M., Crombag, J. J. R., Senden, J. M. G., Waterval, W. A. H., Bierau, J., Verdijk, L. B., & van Loon, L. J. C. (2018). Protein content and amino acid composition of commercially available plant-based protein isolates. *Amino Acids, 50*(12), 1685–1695. https://doi.org/10.1007/s00726-018-2640-5

Guess, N., Klatt, K., Wei, D., Williamson, E., Ulgenalp, I., Trinidade, O., … Mills, C. (2023). A cross-sectional analysis of products marketed as plant-based across the United States, United Kingdom, and Canada using online nutrition information. *Current Developments in Nutrition, 7*(3), Article 100059. https://doi.org/10.1016/j.cdnut.2023.100059

Harnack, L., Mork, S., Valluri, S., Weber, C., Schmitz, K., Stevenson, J., & Pettit, J. (2021). Nutrient composition of a selection of plant-based ground beef alternative products available in the United States. *Journal of the Academy of Nutrition and Dietetics, 121*(12), 2401–2408.e2412. https://doi.org/10.1016/j.jand.2021.05.002

Harnack, L. J., Reese, M. M., & Johnson, A. J. (2022). Are plant-based meat alternative products healthier than the animal meats they mimic? *Nutrition Today, 57*(4), 195–199.

Hartmann, C., Furtwaengler, P., & Siegrist, M. (2022). Consumers' evaluation of the environmental friendliness, healthiness and naturalness of meat, meat substitutes, and other protein-rich foods. *Food Quality and Preference, 97*, Article 104486.

Heerschop, S. N., Kanellopoulos, A., Biesbroek, S., & van 't Veer, P.. (2023). Shifting towards optimized healthy and sustainable Dutch diets: Impact on protein quality. *European Journal of Nutrition, 62*(5), 2115–2128. https://doi.org/10.1007/s00394-023-03135-7

Hercberg, S., Touvier, M., & Salas-Salvado, J. (2021). *The Nutri-score nutrition label*. Hogrefe AG.

Hunt, J. R. (2003). Bioavailability of iron, zinc, and other trace minerals from vegetarian diets. *The American Journal of Clinical Nutrition, 78*(3), 633S–639S.

Katidi, A., Xypolitaki, K., Vlassopoulos, A., & Kapsokefalou, M. (2023). Nutritional quality of plant-based meat and dairy imitation products and comparison with animal-based counterparts. *Nutrients, 15*(2), 401.

Kim, H., Rebholz, C. M., Hegde, S., LaFiura, C., Raghavan, M., Lloyd, J. F., … Seidelmann, S. B. (2021). Plant-based diets, pescatarian diets and COVID-19 severity: A population-based case-control study in six countries. *BMJ Nutrition, Prevention & Health, 4*(1), 257–266. https://doi.org/10.1136/bmjnph-2021-000272

Ložnjak Švarc, P., Jensen, M. B., Langwagen, M., Poulsen, A., Trolle, E., & Jakobsen, J. (2022). Nutrient content in plant-based protein products intended for food composition databases. *Journal of Food Composition and Analysis, 106*, Article 104332. https://doi.org/10.1016/j.jfca.2021.104332

Ma, K. K., Greis, M., Lu, J., Nolden, A. A., McClements, D. J., & Kinchla, A. J. (2022). Functional performance of plant proteins. *Foods, 11*(4), 594. https://www.mdpi.com/2304-8158/11/4/594.

Mariotti, F., & Gardner, C. D. (2019). Dietary protein and amino acids in vegetarian diets-a review. *Nutrients, 11*(11). https://doi.org/10.3390/nu11112661

Mathai, J. K., Liu, Y., & Stein, H. H. (2017). Values for digestible indispensable amino acid scores (DIAAS) for some dairy and plant proteins may better describe protein quality than values calculated using the concept for protein digestibility-corrected amino acid scores (PDCAAS). *British Journal of Nutrition, 117*(4), 490–499.

Matte, J. J., Britten, M., & Girard, C. L. (2014). The importance of milk as a source of vitamin B12 for human nutrition. *Animal Frontiers, 4*(2), 32–37. https://doi.org/10.2527/af.2014-0012

Mayer Labba, I.-C., Steinhausen, H., Almius, L., Bach Knudsen, K. E., & Sandberg, A.-S. (2022). Nutritional composition and estimated Iron and zinc bioavailability of meat substitutes available on the Swedish market. *Nutrients, 14*(19), 3903. https://www.mdpi.com/2072-6643/14/19/3903.

McClements, I. F., & McClements, D. J. (2023). Designing healthier plant-based foods: Fortification, digestion, and bioavailability. *Food Research International, 169*, Article 112853. https://doi.org/10.1016/j.foodres.2023.112853

McMacken, M., & Shah, S. (2017). A plant-based diet for the prevention and treatment of type 2 diabetes. *Journal of Geriatric Cardiology, 14*(5), 342–354. https://doi.org/10.11909/j.issn.1671-5411.2017.05.009

Meade, S. J., Reid, E. A., & Gerrard, J. A. (2005). The impact of processing on the nutritional quality of food proteins. *Journal of AOAC International, 88*(3), 904–922.

Moehn, S., Bertolo, R. F., Pencharz, P. B., & Ball, R. O. (2005). Development of the indicator amino acid oxidation technique to determine the availability of amino acids from dietary protein in pigs. *The Journal of Nutrition, 135*(12), 2866–2870.

Niklewicz, A., Smith, A. D., Smith, A., Holzer, A., Klein, A., McCaddon, A., … CluB.. (2023). The importance of vitamin B(12) for individuals choosing plant-based diets. *European Journal of Nutrition, 62*(3), 1551–1559. https://doi.org/10.1007/s00394-022-03025-4

Nolden, A. A., & Forde, C. G. (2023). The nutritional quality of plant-based foods. *Sustainability, 15*(4), 3324. https://www.mdpi.com/2071-1050/15/4/3324.

Perez-Moral, N., Saha, S., Pinto, A. M., Bajka, B. H., & Edwards, C. H. (2023). In vitro protein bioaccessibility and human serum amino acid responses to white bread enriched with intact plant cells. *Food Chemistry, 404*(Pt A), Article 134538. https://doi.org/10.1016/j.foodchem.2022.134538

Pinckaers, P. J. M., Trommelen, J., Snijders, T., & van Loon, L. J. C. (2021). The anabolic response to plant-based protein ingestion. *Sports Medicine, 51*(1), 59–74. https://doi.org/10.1007/s40279-021-01540-8

Protein and amino acid requirements in human nutrition: Report of a joint FAO/WHO/UNU expert consultation. (2007). Geneva: World Health Organization.

Recommendations, G. D. (2016). *Government recommendations for energy and nutrients for males and females aged 1–18 years and 19+ years (N. S. Team, Trans.)*. London: Public Health England.

Ridoutt, B. (2023). New plant-based and alternative protein foods—Realising the benefits and avoiding the risks. *Nutrition & Dietetics, 80*(2), 223–224. https://doi.org/10.1111/1747-0080.12779

Ridoutt, B. G., Baird, D., & Hendrie, G. A. (2021). The role of dairy foods in lower greenhouse gas emission and higher diet quality dietary patterns. *European Journal of Nutrition, 60*, 275–285.

Ridoutt, B. G., Hendrie, G. A., & Noakes, M. (2017). Dietary strategies to reduce environmental impact: A critical review of the evidence base. *Advances in Nutrition, 8*(6), 933–946.

Rosi, A., Mena, P., Pellegrini, N., Turroni, S., Neviani, E., Ferrocino, I., … Angelino, D. (2017). Environmental impact of omnivorous, ovo-lacto-vegetarian, and vegan diet. *Scientific Reports, 7*(1), 6105.

Rousseau, S., Kyomugasho, C., Celus, M., Hendrickx, M. E., & Grauwet, T. (2020). Barriers impairing mineral bioaccessibility and bioavailability in plant-based foods and the perspectives for food processing. *Critical Reviews in Food Science and Nutrition, 60*(5), 826–843.

Rust, N. A., Ridding, L., Ward, C., Clark, B., Kehoe, L., Dora, M., … Reynolds, C. J. (2020). How to transition to reduced-meat diets that benefit people and the planet. *Science of the Total Environment, 718*, Article 137208.

Rutherfurd, S. M., & Moughan, P. J. (2012). Available versus digestible dietary amino acids. *British Journal of Nutrition, 108*(S2), S298–S305. https://doi.org/10.1017/S0007114512002528

Sadler, C. R., Grassby, T., Hart, K., Raats, M. M., Sokolović, M., & Timotijevic, L. (2022). "Even we are confused": A thematic analysis of Professionals' perceptions of processed foods and challenges for communication. *Frontiers in Nutrition, 9*. https://doi.org/10.3389/fnut.2022.826162

Salomé, M., Huneau, J.-F., Le Baron, C., Kesse-Guyot, E., Fouillet, H., & Mariotti, F. (2021). Substituting meat or dairy products with plant-based substitutes has small and heterogeneous effects on diet quality and nutrient security: A simulation study in French adults (INCA3). *The Journal of Nutrition, 151*(8), 2435–2445.

Santo, R. E., Kim, B. F., Goldman, S. E., Dutkiewicz, J., Biehl, E. M. B., Bloem, M. W., … Nachman, K. E. (2020). Considering plant-based meat substitutes and cell-based meats: A public health and food systems perspective. *Frontiers in Sustainable Food Systems, 4*. https://doi.org/10.3389/fsufs.2020.00134

Schaafsma, G. (2000). The protein digestibility–corrected amino acid score. *The Journal of Nutrition, 130*(7), 1865S–1867S.

Scholz-Ahrens, K. E., Ahrens, F., & Barth, C. A. (2020). Nutritional and health attributes of milk and milk imitations. *European Journal of Nutrition, 59*(1), 19–34. https://doi.org/10.1007/s00394-019-01936-3

Schutyser, M., Pelgrom, P., Van der Goot, A., & Boom, R. (2015). Dry fractionation for sustainable production of functional legume protein concentrates. *Trends in Food Science & Technology, 45*(2), 327–335.

Seves, S. M., Verkaik-Kloosterman, J., Biesbroek, S., & Temme, E. H. M. (2017). Are more environmentally sustainable diets with less meat and dairy nutritionally adequate? *Public Health Nutrition, 20*(11), 2050–2062. https://doi.org/10.1017/S1368980017000763

Singh, S., Gamlath, S., & Wakeling, L. (2007). Nutritional aspects of food extrusion: A review. *International Journal of Food Science & Technology, 42*(8), 916–929.

Sterling, S. R., & Bowen, S. A. (2019). The potential for plant-based diets to promote health among blacks living in the United States. *Nutrients, 11*(12). https://doi.org/10.3390/nu11122915

Swinburn, B. A., Kraak, V. I., Allender, S., Larijani, B., & Tootee, A. (2019). The global -Syndemic of obesity, undernutrition, and climate change: The lancet commission report (vol 393, pg 791, 2019). *Lancet, 393*(10173), 791–846. https://doi.org/10.1016/S0140-6736(18)32822-8

Tachie, C., Nwachukwu, I. D., & Aryee, A. N. A. (2023). Trends and innovations in the formulation of plant-based foods. *Food Production, Processing and Nutrition, 5*(1), 16. https://doi.org/10.1186/s43014-023-00129-0

Tonheim, L. E., Austad, E., Torheim, L. E., & Henjum, S. (2022). Plant-based meat and dairy substitutes on the Norwegian market: Comparing macronutrient content in substitutes with equivalent meat and dairy products. *Journal of Nutritional Science, 11*, Article e9.

Toribio-Mateas, M. A., Bester, A., & Klimenko, N. (2021). Impact of plant-based meat alternatives on the gut microbiota of consumers: A real-world study. *Foods, 10*(9). https://doi.org/10.3390/foods10092040

Tso, R., & Forde, C. G. (2021). Unintended consequences: Nutritional impact and potential pitfalls of switching from animal- to plant-based foods. *Nutrients, 13*(8). https://doi.org/10.3390/nu13082527

Turner-McGrievy, G. M., Barnard, N. D., Cohen, J., Jenkins, D. J. A., Gloede, L., & Green, A. A. (2008). Changes in nutrient intake and dietary quality among participants with type 2 diabetes following a low-fat vegan diet or a conventional diabetes diet for 22 weeks. *Journal of the American Dietetic Association, 108*(10), 1636–1645. https://doi.org/10.1016/j.jada.2008.07.015

Tyndall, S. M., Maloney, G. R., Cole, M. B., Hazell, N. G., & Augustin, M. A. (2022). Critical food and nutrition science challenges for plant-based meat alternative products. *Critical Reviews in Food Science and Nutrition, 1-16*. https://doi.org/10.1080/10408398.2022.2107994

Vanga, S. K., & Raghavan, V. (2018). How well do plant based alternatives fare nutritionally compared to cow's milk? *Journal of Food Science and Technology, 55*(1), 10–20. https://doi.org/10.1007/s13197-017-2915-y

Verduci, E., D'Elios, S., Cerrato, L., Comberiati, P., Calvani, M., Palazzo, S., … Peroni, D. G. (2019). Cow's milk substitutes for children: Nutritional aspects of milk from different mammalian species, special formula and plant-based beverages. *Nutrients, 11*(8), 1739.

van Vliet, S., Bain, J. R., Muehlbauer, M. J., Provenza, F. D., Kronberg, S. L., Pieper, C. F., & Huffman, K. M. (2021). A metabolomics comparison of plant-based meat and grass-fed meat indicates large nutritional differences despite comparable nutrition facts panels. *Scientific Reports, 11*(1), 13828.

Walther, B., Guggisberg, D., Badertscher, R., Egger, L., Portmann, R., Dubois, S., … Zoller, O. (2022). Comparison of nutritional composition between plant-based drinks and cow's milk. *Frontiers in Nutrition, 9*, 2645.

van der Weele, C., Feindt, P., Jan van der Goot, A., van Mierlo, B., & van Boekel, M. (2019). Meat alternatives: An integrative comparison. *Trends in Food Science & Technology, 88*, 505–512. https://doi.org/10.1016/j.tifs.2019.04.018

Weikert, C., Trefflich, I., Menzel, J., Obeid, R., Longree, A., Dierkes, J., … Abraham, K. (2020). Vitamin and mineral status in a vegan diet. *Deutsches Ärzteblatt International, 117*(35–36), 575–582. https://doi.org/10.3238/arztebl.2020.0575

Wickramasinghe, K., Breda, J., Berdzuli, N., Rippin, H., Farrand, C., & Halloran, A. (2021). The shift to plant-based diets: Are we missing the point? *Global Food Security, 29*, Article 100530. https://doi.org/10.1016/j.gfs.2021.100530

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., … Wood, A. (2019). Food in the Anthropocene: The EAT–lancet commission on healthy diets from sustainable food systems. *The Lancet, 393*(10170), 447–492.

Woodside, J. V., & Mullan, K. R. (2021). Iodine status in UK–an accidental public health triumph gone sour. *Clinical Endocrinology, 94*(4), 692–699.