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Environmental and nutritional implications of replacing meat and dairy with alternatives

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The environmental burden of meat and dairy has drawn attention to alternatives, although their capacity to fulfil similar dietary roles remains uncertain. Here, we evaluate the effects of replacing meat and jointly replacing meat and dairy with alternatives on the environmental impacts and nutrient profiles of current and recommended diets. We consolidate environmental inventory and food composition databases in a product- and diet-level analysis to evaluate various impact categories and nutrients. The results show that replacing meat with alternatives can lower environmental impacts by up to 52%, though adequate intake of some critical nutrients, particularly vitamin B12, needs to be ensured. Compared to dairy products, dairy alternatives more frequently lack nutrients, such as calcium and iodine, and certain ingredients, such as almond and coconut, may increase specific environmental impacts. Our findings highlight the challenges of reducing environmental impacts without compromising nutrition, with implications for high-income countries pursuing sustainable dietary transitions.

Human nutrition contributes substantially to anthropogenic environmental impacts through agricultural activities and food processing. Globally, food systems are responsible for approximately a third of greenhouse gas emissions[1,2], and agricultural irrigation represents 70% of freshwater use (www.oecd.org/agriculture/topics/water-and-agriculture). The meat and dairy industries are major contributors to these impacts[1]. In addition to environmental concerns, dietary patterns in high-income countries are commonly characterised by high amounts of ultra-processed foods[3], contributing to public health challenges, such as obesity[4] and non-communicable diseases[3,5,6].

To address these issues, various dietary guidelines have been developed and revised to promote nutritionally adequate and more sustainable eating patterns[4,7–9]. Unfortunately, consumers rarely follow dietary guidelines, whereas they are more likely to adopt specific recommendations[8,10,11]. Since the environmental impacts of human nutrition are largely driven by meat and dairy products, focusing on replacing them offers a lever for achieving considerable improvements through a limited range of dietary changes[8,12–14]. Furthermore, reducing the consumption of red and especially processed meat is associated with decreased health risks[15–18].

In this context, alternatives—that is, substitutes for meat and dairy products—have become increasingly popular. A large variety of alternatives is available on the market or under development[19] (Supplementary Information 2 [SI2], Table T5). At the product level, previous analyses have reported comparatively lower environmental impacts for alternatives. However, these assessments often focus on a limited set of impact categories, such as global warming and land use[20,21]. Including additional impact categories reveals that the environmental outcomes of these alternatives can vary, depending on factors such as the chosen reference product or the alternative's main ingredient[22,23]. Thus, replacing meat and dairy in the diet with different alternatives can have diverse effects on its environmental performance. Animal products are sources of high-quality proteins, minerals (e.g. calcium and iron), and vitamins (e.g. B12). Although some alternatives, such as algae and insects, have nutrient profiles that support their use as meat and dairy alternatives[20], the more widespread plant-based alternatives often differ substantially in nutritional composition compared to their animal-based references[23–25]. Nonetheless, assessing products alone provides limited insight for informing policy and interventions. Understanding their role within diets is essential to evaluating their potential to enable sustainable dietary shifts.

A recent study investigated the ability of novel alternatives to improve the environmental impacts of diets while maintaining nutritional adequacy[26]. It showed that diet optimisation that includes novel alternatives could reduce environmental impacts by over 80%, although several difficulties associated with the potential implementation of the obtained diets are

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highlighted. By contrast, two other studies, one in the Netherlands[27] and the other in Canada[12], focused on more conventional replacements, modifying self-selected diets based on reported intake data from national food consumption surveys. These studies substituted meat and dairy with processed soy-based meat and milk alternatives, and unprocessed nuts, seeds, and legumes. The results indicate that replacing 50% of meat and dairy in Canadian diets could reduce diet-related greenhouse gas emissions by up to 25%, while a complete replacement of meat and dairy in Dutch diets shows a potential for reducing diet-related greenhouse gas emissions by 47% and land use by 41%. However, according to both studies, replacement may also increase the risk of micronutrient deficiencies in the population. This underscores that nutritional adequacy remains a key bottleneck in the suitability of alternatives to replace meat and dairy. Although these studies provide valuable insights, they are limited by the narrow scope of alternatives, excluding a broad range of ingredients on the market (SI2-T5). Moreover, they focused on only a few environmental impact categories. This increases the risk of a burden shift, meaning that reductions in one impact category may lead to increases in unassessed categories.

Overall, research on incorporating existing meat and dairy alternatives into diets remains limited, particularly regarding the variety of nutrients reported[12,27] and their performance in self-selected rather than optimised diets[4,7,9]. This creates a gap in understanding how the broad range of available alternatives can support the short-term shift towards nutritionally adequate and environmentally sustainable diets, and which product characteristics are most consequential. To address this gap, we raise three research questions: (1) How do currently available alternatives compare to their respective references in terms of nutritional value and environmental impacts at the product level? (2) To what extent can replacing meat and dairy with available alternatives affect the nutritional and environmental performance of self-selected and recommended diets? (3) Which product characteristics should guide the development of alternatives to meet the requirements of nutritious and sustainable diets?

To generate novel evidence, we combine product- and diet-level analyses, focusing on four key aspects. First, we assess a broad range of alternatives and their references across multiple environmental impact categories using the Life Cycle Assessment methodology[28,29]. Second, we evaluate a comprehensive set of nutrients to determine whether nutrition remains a major constraint for substitution. Third, we identify the ingredients driving environmental trade-offs. Finally, we analyse self-selected diets to provide realistic insights into short-term substitution strategies. By addressing both environmental and nutritional dimensions, we aim to inform future product development and evidence-based policy interventions. The study focuses on Switzerland, a high-income country characterised by early adoption of nutritional trends, low self-sufficiency in plant-based foods, and high production and consumption of meat and dairy products. Similar patterns are observed in other high-income countries, such as Canada[12] and the Netherlands[8].

Results

Product level

We analysed a diverse set of meat and dairy alternatives, grouped by main ingredients and predominant processing type. Two traditional alternatives, falafel and tofu, were treated separately, since they are well-known standalone products. Additionally, we calculated the average profiles for mechanically texturised plant-based meat alternatives and milk alternatives by aggregating all available data points within each group. The most common meat types and dairy products served as references (Table 1, SI1-1.1).

To illustrate key patterns across products, Fig. 1 combines the nutrient density (Nutrient Rich Foods index[30] NRF11.3) with three environmental indicators that highlight notable differences. All values are expressed per 100 g of product. The results for individual nutrients and additional environmental indicators are provided in SI1, Supplementary Figures and SI2-T3.

Most alternatives exhibited lower environmental impacts than their respective references. Notable exceptions included falafel, insect-based meat alternatives, and several dairy alternatives, which showed higher water scarcity potentials. In particular, almond drinks displayed high water requirements despite their low almond content. Cheese alternatives additionally displayed elevated freshwater eutrophication potential, largely due to their high coconut oil content.

Table 1 | Average and ingredient-specific product groups investigated

Meat alternatives	Dairy alternatives
Plant-based (mechanically texturised), average	Milk alternatives, average
Soy-based (mechanically texturised)	Soy drink
Wheat-based (mechanically texturised)	Oat drink
Legume-based (excl. soy, mechanically texturised)	Almond drink
Falafel	Yoghurt alternatives
Tofu (and tempeh)	Cheese alternatives
Insect-based	Cream alternatives
Mycoprotein-based (Quorn®)	
Meat references	**Dairy references**
Beef (processed and unprocessed)	Cow's milk
Pork (processed and unprocessed)	Yoghurt
Poultry (processed and unprocessed)	Semi-hard cheese
Veal (processed and unprocessed)	Cream

Average groups combine the specific groups below as well as additional data points with either nutrient or environmental information.

Nutrient density scores were generally comparable between meat and dairy alternatives and their respective references, with processed meats and cheese alternatives scoring lower than their counterparts. However, the index conceals substantial variations in individual nutrient levels. Dairy alternatives, especially cheese alternatives, tended to contain less calcium than their references, while most meat alternatives contained more calcium (SI1, Supplementary Figures). Vitamin B12 levels were generally higher in animal-based products. Plant-based alternatives with notable B12 content were fortified. Within product groups, nutrient content and environmental impacts varied by up to 100%, due to differences in formulation, nutrient fortification, raw material origin, and processing conditions. Detailed patterns are reported for soy-based mechanically texturised alternatives in SI1-Supplementary Figure 7.

Additional nutritional and environmental trade-offs emerged in the assessment results not displayed in Fig. 1 and SI1 Supplementary Figures. Soy products and falafel consistently showed high nutrient content, particularly for magnesium and vitamin A. By contrast, mycoprotein-based products were low in iron, iodine, and vitamin E, while dairy alternatives had low levels of calcium, vitamin A, and iodine. Most alternatives contained more fibre, iron, magnesium, and vitamin E but less protein than their references. Land use and terrestrial acidification impacts were generally lower for alternatives.

Diet level

The diet-level implications of substituting meat and dairy with alternatives were evaluated using the average self-selected Swiss diet derived from national food consumption surveys[31] and the recommended Swiss diet[32]. Scenarios included full replacement of meat and both meat and dairy. The standard alternatives for substitution were the average plant-based mechanically texturised meat alternatives and the average milk alternatives. Each product group was also assessed individually to define the range of potential results. Dietary reference values from the European Food Safety Authority (EFSA) and the Swiss Federal Food Safety and Veterinary Office (BLV) served as nutrient thresholds (SI2-T6). For the environmental dimension, the impacts of the recommended diet were used as references.

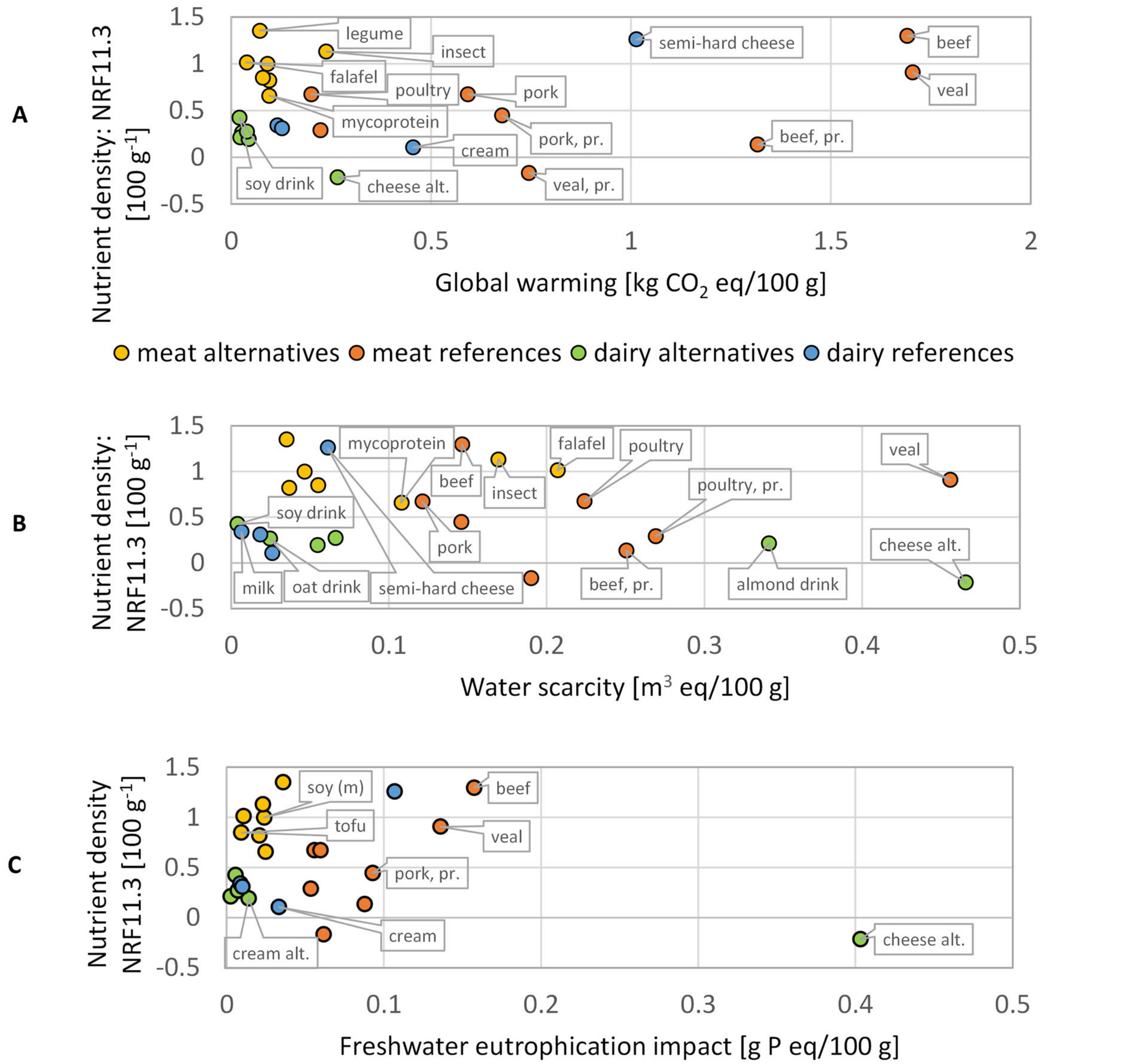

Fig. 1 | Product comparison across nutrient density (NRF11.3) and three environmental impact categories. **A** Global warming, **B** Water scarcity, and **C** Freshwater eutrophication. Selected products are labelled for reference. More detailed data are provided in SI2-T3 and SI3. pr. – processed, alt. – alternative, m – mechanically texturised.

In the recommended diet, dairy intake was higher and meat intake lower than in the self-selected diet (Fig. 2). Other notable differences included higher intake of vegetables, nuts and seeds and lower intake of alcoholic beverages, seafood, fruits, and food grouped as 'other', such as snacks and sweets in the recommended diet. Overall, the recommended diet showed a higher content of qualifying nutrients, lower levels of disqualifying nutrients, greater nutrient density, and reduced environmental impacts (Fig. 3).

In the absence of meat, dairy, or their alternatives, both reference diets provided adequate amounts of vitamins A, C, and E. When we considered the average requirement threshold, the same was true for fibre, protein, and iron. The recommended diet also contained adequate levels of magnesium and potassium. Hence, these nutrients were not limiting, regardless of substitution. By contrast, calcium, iodine, and vitamin B12 reached only 36%, 59%, and 47%, respectively, of their reference values in the absence of meat, dairy, or their alternatives. Replacing dairy lowered the content of all three nutrients, whereas replacing meat reduced only the levels of vitamin B12. The apparent inadequacy of iodine and vitamin B12 in the recommended diet that included meat and dairy was caused by model limitations, such as the use of muscle meat averages and unknown levels of salt iodisation (see SI1-2.2). Among the disqualifying nutrients, the content of saturated fatty acids decreased in both substitution scenarios. Sodium content varied widely, depending on the alternative used for the substitution, with meat alternatives showing a range equivalent to 20% of the adequate intake (Fig. 3B). Dairy alternatives contained more added sugar than their respective references.

For the environmental dimension, the results were comparably clear. Meat substitution reduced all assessed environmental impacts (Fig. 3C). Dairy substitution similarly reduced global warming, land occupation, and terrestrial acidification but increased water scarcity and freshwater eutrophication. However, these increases were primarily driven by specific ingredients. Almonds, and to a lesser extent oats, contributed to water scarcity, while high coconut oil content in cheese alternatives raised freshwater eutrophication (see also Fig. 1).

Sensitivity analysis

The choice of the alternative product influenced both the nutritional value and the environmental impacts of the diets. However, the relative ranking of diets in terms of environmental impacts was rarely affected (ranges in Fig. 3). At the product level, both ingredient composition and raw material origin influenced the results. For example, among mechanically texturised soy-based meat alternatives, product formulation altered global warming

Food group [g/(person*day)]	self-selected diet: reference	self-selected diet: no meat	self-selected diet: no meat, no dairy	recommended diet: reference	recommended diet: no meat	recommended diet: no meat, no dairy
Meat	**124**			**47**		
Meat alternatives		**124**	**124**		**47**	**47**
Dairy	**259**	**259**		**387**	**387**	
Dairy alternatives			**259**			**387**
Non-alcoholic beverages[1]		813			605	
Alcoholic beverages		267			46	
Eggs		16			21	
Oils and fats		22			30	
Seafood		36			16	
Fruits		200			188	
Vegetables (incl. legumes)		193			440	
Cereal products		240			248	
Potatoes and tubers		82			120	
Nuts and seeds		9			25	
Other foods		213			47	

[1]*not including water*

Fig. 2 | Food group composition of the investigated diets in g per person and day. In the diet icons, meat appears in red, meat alternatives in yellow, dairy products in blue, and dairy alternatives in green.

impacts by up to 37% and NRF11.3 scores by up to 11% (SI2-T8). Different soybean origins led to variations in global warming impacts of up to 60% (SI2-T9). Nevertheless, this variation within product groups remained minor compared to the differences between alternatives and references, the latter showing 2.5–19 times higher global warming impacts and 8–117% lower nutrient density scores (SI2-T8), with the exception of unprocessed beef, which had a higher NRF11.3 score. Thus, the act of replacing meat and dairy generally had a greater influence on the nutritional and environmental performance than the specific composition or origin of the chosen alternative.

Discussion

Our findings indicate that replacing meat and dairy products with currently available alternatives, on a mass-equivalent basis, is associated with lower modelled environmental impacts in most categories. This is consistent with prior modelling studies linking substitutions of high-impact animal products to notably lower impacts on global warming and land occupation associated with human diets[33]. In high-income countries, emission reduction potentials of up to 50% have been reported[13,14]. Previous studies have indicated that the production of plant-based foods is associated with a lower acidification potential than that of meat and dairy products[1]. In our study's models, replacing meat and dairy with alternatives reduced the impacts on global warming, terrestrial acidification, and land occupation by up to 44%, 54%, and 40%, respectively, in the self-selected diet. Similar reductions of up to 38%, 47%, and 31% were found for the recommended diet.

In our assessment, substitution had only minor effects on water scarcity impacts, due to the contribution of other food groups. Many plant-based foods consumed in Switzerland are imported from regions where irrigation is common and water is a limiting resource. Given Switzerland's low water scarcity characterisation factor[34], these imported foods contribute disproportionately to the overall water scarcity score. This effect also explains the observed increase in water scarcity when dairy products are substituted, as dairy alternatives often rely on ingredients requiring irrigation, such as almonds and coconuts. Modelled freshwater eutrophication decreased with meat substitution but increased with dairy replacement, the latter primarily driven by the refined coconut oil used in cheese alternatives. The production of coconut oil is associated with high nutrient emissions in existing life cycle inventories, resulting in elevated eutrophication impacts when characterised in our assessment. However, due to the limited availability of complete processing data for cheese alternatives, only three were included. Thus, these results are sensitive and may change as more comprehensive data become available.

Since most alternatives showed lower modelled environmental impacts than their references, their suitability as alternatives depends primarily on nutritional adequacy. While product-level analyses revealed notable differences in nutrient composition, their relevance can only be assessed in the context of whole diets. Our findings suggest that most nutrient requirements can be met without meat and dairy, or their alternatives. Exceptions are iodine, calcium, and vitamin B12, which are commonly low in alternatives, especially dairy alternatives, which contribute to reduced dietary intake of these nutrients in replacement scenarios, as shown in our study and previous research[24,27,35,36]. Because the remainders of the diets were not modified beyond the replacements, these reductions are not compensated by other foods, making them particularly relevant for population groups with elevated requirements or deficiency risks[37–39]. Whereas vitamin B12 is commonly supplemented by at-risk indiviuals[40], calcium and iodine are

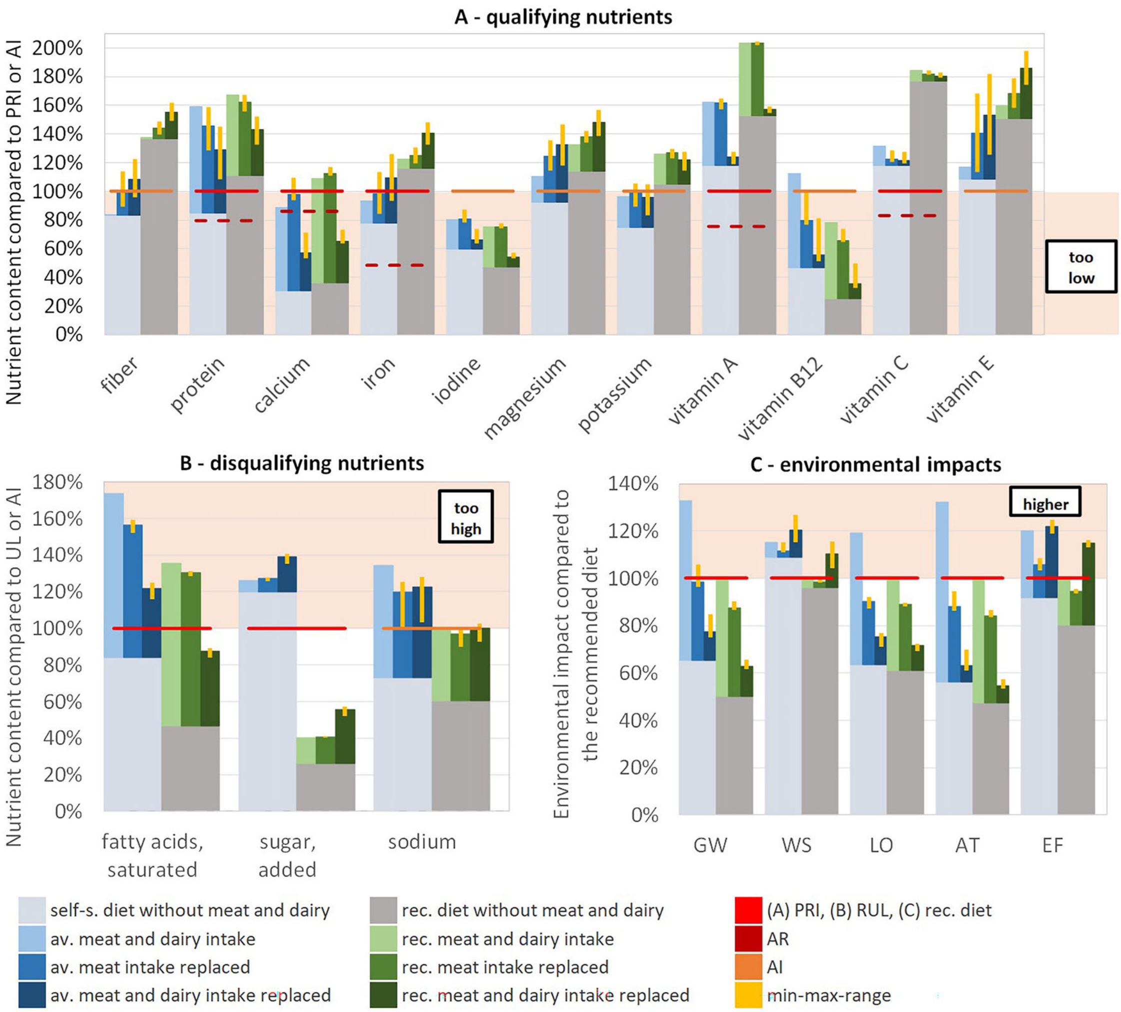

Fig. 3 | Nutritional and environmental comparisons of the assessed diets across. **A** qualifying nutrients, **B** disqualifying nutrients, and **C** environmental impacts. Reference lines indicate nutrient and environmental thresholds. For qualifying nutrients, a dotted line denotes the average requirement (AR) for nutrients with the population reference intake (PRI) as the 100% reference. Yellow ranges represent the minimum and maximum values obtained by including individual alternative product groups in each diet. GW – global warming, WS – water scarcity, LO – land occupation, agricultural, AT – acidification, terrestrial, EF – eutrophication, freshwater, av. – average, rec. – recommended, self-s. – self-selected, AI – adequate intake, RUL – recommended upper intake level.

frequently fortified in foods[36,41], yet both remain nutrients of concern in the population[42,43]. Adapting fortification strategies to better align consumption patterns could help mitigate these risks[41,44–46]. However, bioavailability should be considered, as it can be limited in alternatives with fortified nutrients[47].

Overall, dairy alternatives were less often able to nutritionally substitute their reference products, but they showed the potential to reduce the intake of saturated fatty acids and increase the intake of fibre, iron, magnesium, and vitamin E. Although legumes, vegetables and fruits can also contribute these nutrients, they generally share the same limitations as dairy alternatives in providing calcium, iodine, and vitamin B12. Hence, while meat alternatives may generally improve nutritional intake if the lower B12 content is addressed, dairy alternatives can support dietary diversification. Similar synergies and trade-offs apply to the environmental impacts, where meat replacement generally lowered impacts, while dairy alternatives require more careful selection to ensure overall improvement.

Among the product groups investigated, a large variability in nutrient content was observed. This presents a barrier for consumers aiming to choose suitable products, as making informed decisions considering all relevant nutrients would require more time and knowledge than is typically available during food shopping[48]. Different labels have been introduced to facilitate quick and informed consumer decisions[49,50], but none have achieved broad acceptance.

The sensitivity analyses highlighted the relevance of ingredient choices to both the nutritional value and the environmental impacts of the alternatives. From an environmental perspective, the ingredient type and origin of raw materials, including production practices and yields, may affect the impact categories. Nutritionally, the product formulation had a large influence. Previous studies have shown that combining cereal- and legume-based proteins can increase protein quality[51], whereas poor combinations may reduce bioavailability and increase the risk of malnutrition[52]. This latter is often highlighted in the context of ultra-high food processing[5]. Overall, these results highlight the need for alternative product development to prioritise balanced formulations, targeted fortification, and lower-impact ingredients to support sustainable and nutritionally adequate diets. These priorities may also inform regulatory frameworks, such as fortification standards, sustainable sourcing guidelines, and labelling requirements.

Despite the careful selection of methods, several limitations should be acknowledged. Cooking and food preparation were not modelled, although major food weight changes due to cooking (e.g. water absorption in pasta and rice) and losses at the consumer stage were accounted for. Preparation methods can influence both environmental impacts and nutrient availability. For example, meat products often require more energy-intensive cooking than their alternatives, while nutrient retention or degradation can occur in all foods, depending on the preparation method and food matrix[53] (see SI1-2.2). Nutrient bioavailability, particularly relevant when comparing animal- and plant-based food, was not considered due to limited data availability and its dependence on the food matrix[52,54]. The nutrient adequacy assessment is further constrained by the ongoing debate around the reference intake values of several nutrients, which may change in the future[55,56]. On the environmental side, uncertainty stems from the limited availability of comprehensive production data for some of the products, such as tempeh and insect- and mycoprotein-based meat alternatives, as well as cheese, cream, and yoghurt alternatives. In addition, environmental and nutrient composition data were based on average values to reflect population-level dietary patterns. Real-world variability across production systems and product formulations is therefore not fully captured, and for conventional meat and dairy products, differences with alternatives may vary substantially at the individual product level. As dietary recommendations, consumption patterns, and product formulations evolve, future assessments will be essential to validate and update our findings.

Conclusion

Our study provides insights into the role of currently available alternative products in supporting the transition towards more sustainable and nutritionally adequate diets. Our models reveal that although many of the assessed alternatives show favourable environmental profiles and can contribute positively to nutrient intake, they vary widely in composition and are not inherently adequate substitutes for their animal-based counterparts. To fully realise their potential, product development should prioritise nutritionally balanced formulations, targeted fortification that accounts for bioavailability, and the use of low-impact ingredients. Replacing meat and dairy entirely represents a substantial dietary change and requires informed product selection to avoid nutritional inadequacies and environmental trade-offs. Greater value chain transparency can encourage decisions in favour of both the environment and nutrition by all relevant stakeholders. Although our assessment focuses on Switzerland, reflecting a specific high-income dietary context, the findings illustrate how combining product- and diet-level data can reveal the nutritional and environmental consequences of dietary shifts. Future studies could apply this approach, linking food consumption, nutrient composition, and environmental data, to evaluate dietary shifts in other national contexts or population groups, and to inform evidence-based product development, innovation, and policy strategies.

Methods

The model is based on the Swiss context, since it is an exemplary market for early adoption of nutritional and dietary trends (high income, innovative, well interconnected, high awareness of environmental issues and animal welfare, good data availability, large share of imported foods). Only data on already purchasable alternative products in Switzerland were included in the investigation. To ensure relevance and avoid assumptions that could decrease the accuracy of our results, no preliminary or laboratory data were considered. The products were compared directly based on weight (as described in the literature[12]).

Datasets on alternatives were selected based on availability, as described below. A market analysis confirmed that the included datasets reflected the range of products available in Switzerland (SI2-T5). Weighted averages were not calculated, as the analysis captured product availability but not sales volumes.

Meat and dairy, and alternatives at the product level – Grouping

The products were grouped to facilitate analysis. The groups were based on their reference product, main ingredient, and type of processing, which we defined as the main method used to transform the raw ingredients into the final product. Each group contained between 1 and 20 individual datasets for the nutrient composition and the environmental assessment, respectively. Generally, more nutrient data than environmental data were available. We did not use common categorisation systems, such as NOVA[5] or the Good Food Institute (www.gfi.org/investment) classification, since they would categorise most products into the same group, preventing a detailed analysis.

Single datasets that could not be associated with an ingredient-specific group were included in two broader groups: (1) plant-based and mechanically texturised meat alternatives, and (2) milk alternatives. Due to limited data, yoghurt, cheese, and cream alternatives could not be grouped based on raw material or processing type. The average nutrient content and environmental impacts were calculated for each group as unweighted mean values of the available datasets.

Meat and dairy, and alternatives at the product level – Nutrient data

Nutrient data at the product level were retrieved from the EuroFIR platform (www.eurofir.org), which provides harmonised access to national food composition databases. Through the platform, data from France, Greece, Portugal, Slovenia, Spain, Switzerland, and the United Kingdom were accessed. These countries were selected based on the availability of data for alternatives and to complement the Swiss database in that regard. Meat and dairy products were taken exclusively from the Swiss database. This ensured sufficient data for the relevant products while maintaining regional focus. Suitable datasets were identified by searching for appropriate terms and filtering the metadata (SI1-1.3.1). The process was repeated twice to ensure completeness. Raw products were selected for consistency, since the preparation of the products can have large consequences for nutrient composition as well as environmental impacts and is highly dependent on individual consumer food preparation habits[57–59]. The inclusion of the preparation stage would likely have added large uncertainty to the results. Moreover, energy use during preparation is typically higher for meat, which requires more thorough cooking, than for many alternatives that are often highly convenient and require minimal heating. Thus, excluding preparation yields a conservative comparison that avoids overstating the benefits of alternatives due to assumptions about cooking practices. For nutrients, the effects of cooking are highly variable, depending on both the method and the nutrient in question. Given this complexity and the lack of standardised preparation practices, systematic integration was not feasible.

Some of the selected datasets were incomplete. In these cases, they were complemented using literature values, average values from similar datasets, or informed assumptions (see SI1-1.3.4 and 1.3.5). Due to a lack of data on insect-based, pea-based, and mycoprotein-based alternatives, new datasets were created from the literature and data provided by the U.S. Department of Agriculture (fdc.nal.usda.gov) (SI1-1.3.6).

Nutrient density was assessed using the NRF index, a widely applied method well suited for LCAs that integrate the nutritional dimension. Originally developed by Fulgoni et al.[30], the NRF has since been adapted and applied in various food system studies[23,60–63]. In this study, we applied the NRF11.3 variant, which offered a balance between comprehensiveness and data availability for our dataset and objectives. The nutrient selection was tailored to reflect Swiss dietary concerns and the specific context of meat and dairy alternatives. Iodine was added due to its known risk of deficiency in Switzerland[64,65], while vitamin B12 and calcium were included for their relevance in comparing animal-based and alternative products. Sugar and sodium were included as disqualifying nutrients, consistent with rising intake concerns and their public health significance[5,6]. Nutrient contributions were expressed relative to dietary reference values consistent with those used for the diet-level analysis, with sex-specific recommendations averaged to represent population-level requirements (SI2-T6).

Meat and dairy, and alternatives at the product level – Environmental data

To assess the environmental impacts of meat and dairy and their alternatives at the product level, life cycle inventories were taken from different databases, including Agribalyse v3.1, AgriFootprint v6.3, ecoinvent v3.9.1, SALCA (Swiss Agricultural LCA) v3.4 and v4.0, and World Food LCA Database (WFLDB) v3.5. The life cycle inventory selection process included a term search comparable to the one for nutrient data (SI1-1.4.1), as well as filtering based on metadata. The process was repeated independently by two researchers to ensure completeness. To complement the selection of products, additional inventories were created based on the literature and publicly available product data (SI1-1.4.2). Most of the final selections of inventories were based on European background data. The system boundaries were set from cradle to production gate, since packaging, retail, and consumption were assumed to be similar between alternative and reference products, hence not affecting the comparison between them. Environmental impacts were calculated in SimaPro v9.6 by applying the SALCA v2.01 method[66]. Group averages were obtained using unweighted mean values. The results for additional impact categories are presented in SI2-T3.

Diet level – Food consumption data

Two diets were chosen as references: the Swiss self-selected diet and the Swiss recommended diet for the adult population. The self-selected diet was based on 24-h food consumption recall questionnaires[31]. Given the large number of food items reported, a selection procedure was applied to reduce complexity while maintaining representativeness, resulting in 104 food items used for modelling. The remaining food items were accounted for via proxies (see SI1-1.2.1).

Although the consumption data were based on the most recent national nutrition survey available for Switzerland, we acknowledge its age as a limitation. To improve validity, meat consumption was updated based on reported sales trends[67], adjusting product proportions while keeping the total intake constant. Dairy consumption data were cross-checked with national purchase statistics[68]. These comparisons showed stable overall dairy intake, with a gradual decline in milk intake but a recent increase in cheese consumption. However, due to inconsistencies between purchase and consumption data, no adjustments to product proportions were made, as such changes would have been uncertain.

The recommended diet was based on Swiss dietary recommendations, which are visualised in the 'Swiss food pyramid'[32]. Explicit recommendations were translated into consumption amounts. If the recommendations were only food group-specific, the composition of the food group was assumed to be identical to the self-selected diet. If this was not possible, the amounts were divided among the available food items, following the principle of a balanced diet (SI1-1.2.2).

Alternative diets were based on the total replacement of meat or both meat and dairy. This approach was chosen to illustrate the largest possible adoption of alternative products, as the consequence of any partial substitution can then be derived from linear equations. To limit the variety of diets presented, the substitution of meat is shown individually but not the substitution of dairy products. Moreover, the reduction of meat consumption is advisable from both a health and an environmental perspective, while the reduction of dairy is mainly advisable from an environmental perspective. The incorporation of meat and dairy alternatives into the diets assumed a 1:1 replacement by weight[12,27].

To calculate the nutrient composition and environmental impacts of the alternative diets, the average product groups were used as a standard for replacement, that is, plant-based and mechanically texturised meat alternatives, milk alternatives, cheese alternatives, cream alternatives, and yoghurt alternatives.

Diet level – Nutrient data

The nutrient composition data for food products other than the alternatives were taken from the EuroFIR dataset for Switzerland. Datasets that best represented the relevant foods we previously identified were selected through targeted searches. All food items were considered raw to minimise uncertainty due to individual food preparation practices. The selection of nutrient thresholds depended on the availability of reference values. Population Reference Intakes (PRIs) and Average Requirements were used as reference values for nutrient adequacy where available, while Adequate Intakes (AIs) were applied when no PRI was defined. For nutrients recommended to be limited, Recommended Upper Intake Levels were used where available. Otherwise, the AI served as a pragmatic reference (SI2-T6). When reference values differed by sex, the average of female and male recommendations was used to represent population-level requirements.

Diet level – Environmental data

Environmental data were extracted from several sources to ensure suitability. Swiss raw material production was modelled based on internal data[69] and ecoinvent inventories. If no Swiss inventory was available, a suitable proxy was identified. The processing steps for food items in Switzerland were modelled by adapting suitable inventories from external databases—that is, Agribalyse, ecoinvent, and WFLDB—to Swiss production conditions (SI1-1.4.5). For each food item, the self-sufficiency of production (i.e., the ratio between Swiss production and total consumption) was considered[70]. Hence, import inventories were created. Here, the import mixes by country of origin were accounted for (SI1-1.4.6). All available environmental data within the Agribalyse, Agri-Footprint, ecoinvent, SALCA, and WFLDB databases were considered to create the import inventories. Within inventories for processes taking place outside of Switzerland, background data and elemental flows were regionalised according to the country of origin of the food item. The system boundaries were set at the cradle-to-production gate for Swiss production and at entry into Switzerland for imported food. Since the diets were based on consumption data, food losses and waste occurring between the production gate and the consumption were accounted for, as they increased the required production volume[71]. Additionally, weight adjustments for water absorption during cooking, such as for rice and pasta, were applied to align the reported consumption weights with the raw material weights used in environmental modelling. Economic allocation was the preferred measure for dividing environmental impacts into multifunctional processes.

For the analysis, the environmental impacts of the diets were compared to those of the reference diet. Currently, there are no established reference values for maximum dietary environmental impacts comparable to dietary reference intakes. Nonetheless, approaches to defining absolute environmental sustainability have been proposed[72]. The selection of the presented impact categories was based on their relevance in the food Life Cycle Assessment literature[1]. The results for additional impact categories are provided in SI2-T4.

Sensitivity analyses

The robustness of the findings was evaluated through sensitivity analyses. To assess the influence of product choice, the nutrient content and environmental impacts of the alternative diets were calculated individually, assuming total replacement with only one product group at a time. The observed sensitivity of the diet-level results is depicted graphically as ranges in Fig. 3. The origin of the raw materials as an uncertainty factor was additionally investigated for an exemplary product. The product was chosen based on the availability of matching nutrient and environmental data, as well as a high content of the main ingredient. The input flow of the main ingredient was replaced with the same raw material from six different locations on four continents. Lastly, the effect of the products' composition was investigated. For that purpose, individual products from the largest product group, the mechanically texturised soy-based alternatives, were analysed for their ingredient composition and put into direct comparison with the group's average performance. The results of the sensitivity analyses are provided in SI2-T8 and T9.

Data availability

The supplementary information is accessible at the Zenodo repository: https://doi.org/10.5281/zenodo.11393922 and also attached to this publication. The cited files are: Supplementary Information 1 (SI1) "*Mehner et al._20260313_Supplementary Information_1_vF*", Supplementary Information (corresponding to supplementary data) 2 (SI2) "*Mehner et al._20260313_Supplementary Information_2_vF*".

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References

1. Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992, https://doi.org/10.1126/science.aaq0216 (2018).
2. Crippa, M. et al. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food* **2**, 198–209, https://doi.org/10.1038/s43016-021-00225-9 (2021).
3. Schneider, K. R. et al. The state of food systems worldwide in the countdown to 2030. *Nat. Food* **4**, 1090–1110, https://doi.org/10.1038/s43016-023-00885-9 (2023).
4. Willett, W. et al. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* **393**, 447–492, https://doi.org/10.1016/s0140-6736(18)31788-4 (2019).
5. Monteiro, C. A., Cannon, G., Lawrence, M., Louzada, M. d. C. & Machado, P. P. Ultra-processed foods, diet quality, and health using the NOVA classification system. *Rome: FAO* **48** (2019).
6. Rauber, F. et al. Ultra-processed food consumption and chronic non-communicable diseases-related dietary nutrient profile in the UK (2008–2014). *Nutrients* **10**, 587, https://doi.org/10.3390/nu10050587 (2018).
7. von Ow, A., Waldvogel, T. & Nemecek, T. Environmental optimization of the Swiss population's diet using domestic production resources. *Journal of Cleaner Production* **248** (2020). https://doi.org/10.1016/j.jclepro.2019.119241.
8. Kramer, G. F. H., Tyszler, M., Veer, P. vt & Blonk, H. Decreasing the overall environmental impact of the Dutch diet: how to find healthy and sustainable diets with limited changes. *Public Health Nutr.* **20**, 1699–1709, https://doi.org/10.1017/S1368980017000349 (2017).
9. Lucas, E., Guo, M. & Guillén-Gosálbez, G. Optimising diets to reach absolute planetary environmental sustainability through consumers. *Sustain. Prod. Consum.* **28**, 877–892, https://doi.org/10.1016/j.spc.2021.07.003 (2021).
10. de Abreu, D. et al. Low compliance with dietary recommendations for food intake among adults. *Clin. Nutr.* **32**, 783–788, https://doi.org/10.1016/j.clnu.2012.11.022 (2013).
11. Schneid Schuh, D., Guessous, I., Gaspoz, J.-M., Theler, J.-M. & Marques-Vidal, P. Twenty-four-year trends and determinants of change in compliance with Swiss dietary guidelines. *Eur. J. Clin. Nutr.* **73**, 859–868, https://doi.org/10.1038/s41430-018-0273-0 (2019).
12. Auclair, O., Eustachio Colombo, P., Milner, J. & Burgos, S. A. Partial substitutions of animal with plant protein foods in Canadian diets have synergies and trade-offs among nutrition, health and climate outcomes. *Nat. Food* **5**, 148–157, https://doi.org/10.1038/s43016-024-00925-y (2024).
13. Rose, D., Willits-Smith, A. M. & Heller, M. C. Single-item substitutions can substantially reduce the carbon and water scarcity footprints of US diets. *Am. J. Clin. Nutr.* **115**, 378–387, https://doi.org/10.1093/ajcn/nqab338 (2022).
14. Willits-Smith, A., Aranda, R., Heller, M. C. & Rose, D. Addressing the carbon footprint, healthfulness, and costs of self-selected diets in the USA: a population-based cross-sectional study. *Lancet Planet. Health* **4**, e98–e106, https://doi.org/10.1016/S2542-5196(20)30055-3 (2020).
15. Fadnes, L. T., Okland, J. M., Haaland, O. A. & Johansson, K. A. Estimating impact of food choices on life expectancy: A modeling study. *PLOS Medicine* **19** (2022). https://doi.org/10.1371/journal.pmed.1003889.
16. Biesbroek, S. et al. Reducing our environmental footprint and improving our health: greenhouse gas emission and land use of usual diet and mortality in EPIC-NL: a prospective cohort study. *Environ. Health* **13**, 27. https://doi.org/10.1186/1476-069X-13-27 (2014).
17. Boada, L. D., Henríquez-Hernández, L. A. & Luzardo, O. P. The impact of red and processed meat consumption on cancer and other health outcomes: Epidemiological evidences. *Food Chem. Toxicol.* **92**, 236–244, https://doi.org/10.1016/j.fct.2016.04.008 (2016).
18. Godfray, H. C. J. et al. Meat consumption, health, and the environment. *Science* **361**, eaam5324, https://doi.org/10.1126/science.aam5324 (2018).
19. Lurie-Luke, E. Alternative protein sources: science powered startups to fuel food innovation. *Nat. Commun.* **15**, 4425. https://doi.org/10.1038/s41467-024-47091-0 (2024).
20. Parodi, A. et al. The potential of future foods for sustainable and healthy diets. *Nat. Sustainability* **1**, 782–789, https://doi.org/10.1038/s41893-018-0189-7 (2018).
21. Mejia, M. et al. Life cycle assessment of the production of a large variety of meat analogs by three diverse factories. *J. Hunger Environ. Nutr.* **15**, 699–711, https://doi.org/10.1080/19320248.2019.1595251 (2019).
22. Detzel, A. et al. Life cycle assessment of animal-based foods and plant-based protein-rich alternatives: an environmental perspective. *J. Sci. Food Agric* https://doi.org/10.1002/jsfa.11417 (2020).
23. Herrmann, M. et al. A comparative nutritional life cycle assessment of processed and unprocessed soy-based meat and milk alternatives including protein quality adjustment. *Frontiers in Sustainable Food Systems* **8** (2024). https://doi.org/10.3389/fsufs.2024.1413802.
24. Walther, B. et al. Comparison of nutritional composition between plant-based drinks and cow's milk. *Front. Nutr.* **9**, 2645, https://doi.org/10.3389/fnut.2022.988707 (2022).
25. Sterup Moore, S., Costa, A., Pozza, M., Weaver, C. M. & De Marchi, M. Nutritional scores of milk and plant-based alternatives and their difference in contribution to human nutrition. *LWT* **191**, 115688, https://doi.org/10.1016/j.lwt.2023.115688 (2024).
26. Mazac, R. et al. Incorporation of novel foods in European diets can reduce global warming potential, water use and land use by over 80. *Nat. Food* **3**, 286–293, https://doi.org/10.1038/s43016-022-00489-9 (2022).
27. Seves, S. M., Verkaik-Kloosterman, J., Biesbroek, S. & Temme, E. H. Are more environmentally sustainable diets with less meat and dairy nutritionally adequate? *Public Health Nutr.* **20**, 2050–2062, https://doi.org/10.1017/S1368980017000763 (2017).
28. International Standard Organisation (ISO). in *Environmental management — Life cycle assessment — Requirements and guidelines* 1-46 (International Standard Organisation (ISO), Geneva, 2006).
29. International Standard Organisation (ISO). in *Environmental management — Life cycle assessment — Principles and framework* 1-20 (International Standard Organisation (ISO), Geneva, 2006).
30. Fulgoni, V. L. 3rd, Keast, D. R. & Drewnowski, A. Development and validation of the nutrient-rich foods index: a tool to measure nutritional quality of foods. *J. Nutr.* **139**, 1549–1554, https://doi.org/10.3945/jn.108.101360 (2009).
31. BLV. *menuCH - Nationale Ernährungserhebung* (Bundesamt für Lebensmittelsicherheit und Veterinärwesen (BLV), 2014). https://www.blv.admin.ch/blv/de/home/lebensmittel-und-ernaehrung/ernaehrung/menuCH.html.
32. SGE. Schweizer Lebensmittelpyramide. (Schweizer Gesellschaft für Ernährung, Bern, 2020).
33. Kozicka, M. et al. Feeding climate and biodiversity goals with novel plant-based meat and milk alternatives. *Nat. Commun.* **14**, 5316. https://doi.org/10.1038/s41467-023-40899-2 (2023).
34. Boulay, A.-M. et al. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). *Int. J. Life Cycle Assess.* **23**, 368–378, https://doi.org/10.1007/s11367-017-1333-8 (2018).

35. Tso, R. & Forde, C. G. Unintended consequences: nutritional impact and potential pitfalls of switching from animal- to plant-based foods. *Nutrients* **13** (2021). https://doi.org/10.3390/nu13082527.
36. Chalupa-Krebzdak, S., Long, C. J. & Bohrer, B. M. Nutrient density and nutritional value of milk and plant-based milk alternatives. *Int. Dairy J.* **87**, 84–92, https://doi.org/10.1016/j.idairyj.2018.07.018 (2018).
37. Zimmermann, M. B., Gizak, M., Abbott, K., Andersson, M. & Lazarus, J. H. Iodine deficiency in pregnant women in Europe. *Lancet Diab. Endocrinol.* **3**, 672–674, https://doi.org/10.1016/S2213-8587(15)00263-6 (2015).
38. Grossklaus, R., Liesenkötter, K.-P., Doubek, K., Völzke, H. & Gaertner, R. Iodine deficiency, maternal hypothyroxinemia and endocrine disrupters affecting fetal brain development: a scoping review. *Nutrients* **15**, 2249, https://doi.org/10.3390/nu15102249 (2023).
39. Rautiainen, S., Manson, J. E., Lichtenstein, A. H. & Sesso, H. D. Dietary supplements and disease prevention — a global overview. *Nat. Rev. Endocrinol.* **12**, 407–420, https://doi.org/10.1038/nrendo.2016.54 (2016).
40. Schüpbach, R., Wegmüller, R., Berguerand, C., Bui, M. & Herter-Aeberli, I. Micronutrient status and intake in omnivores, vegetarians and vegans in Switzerland. *Eur. J. Nutr.* **56**, 283–293, https://doi.org/10.1007/s00394-015-1079-7 (2017).
41. Dold, S. et al. Universal salt iodization provides sufficient dietary iodine to achieve adequate iodine nutrition during the first 1000 days: a cross-sectional multicenter study. *J. Nutr.* **148**, 587–598, https://doi.org/10.1093/jn/nxy015 (2018).
42. Ittermann, T. et al. Standardized map of iodine status in europe. *Thyroid®* **30**, 1346–1354, https://doi.org/10.1089/thy.2019.0353 (2020).
43. Shlisky, J. et al. Calcium deficiency worldwide: prevalence of inadequate intakes and associated health outcomes. *Ann. N. Y. Acad. Sci.* **1512**, 10–28, https://doi.org/10.1111/nyas.14758 (2022).
44. BAG. Massnahmen zur Jodversorgung in der Schweiz. (Bundesamt für Gesundheit, 2013).
45. Wessells, K. R., Manger, M. S., Tsang, B. L., Brown, K. H. & McDonald, C. M. Mandatory large-scale food fortification programmes can reduce the estimated prevalence of inadequate zinc intake by up to 50% globally. *Nat. Food* **5**, 625–637, https://doi.org/10.1038/s43016-024-00997-w (2024).
46. Taeger, M. & Thiele, S. Replacement of Milk and Dairy Products with Soy-Based Alternatives–How to Avoid Nutrient Deficiencies in a Milk-Free Diet? *J. Nutr.* **154**, 163–173, https://doi.org/10.1016/j.tjnut.2023.11.003 (2024).
47. Muleya, M., F. Bailey, E. & H. Bailey, E. A comparison of the bioaccessible calcium supplies of various plant-based products relative to bovine milk. *Food Res. Int.* **175**, 113795, https://doi.org/10.1016/j.foodres.2023.113795 (2024).
48. Graham, D. J. & Jeffery, R. W. Predictors of nutrition label viewing during food purchase decision making: an eye tracking investigation. *Public Health Nutr.* **15**, 189–197, https://doi.org/10.1017/S1368980011001303 (2012).
49. Merz, B. et al. Nutri-Score 2023 update. *Nat. Food* **5**, 102–110, https://doi.org/10.1038/s43016-024-00920-3 (2024).
50. Song, J. et al. Impact of color-coded and warning nutrition labelling schemes: A systematic review and network meta-analysis. *PLOS Med.* **18**, e1003765, https://doi.org/10.1371/journal.pmed.1003765 (2021).
51. Herreman, L., Nommensen, P., Pennings, B. & Laus, M. C. Comprehensive overview of the quality of plant- and animal-sourced proteins based on the digestible indispensable amino acid score. *Food Sci. Nutr.* **8**, 5379–5391, https://doi.org/10.1002/fsn3.1809 (2020).
52. McClements, I. F. & McClements, D. J. Designing healthier plant-based foods: Fortification, digestion, and bioavailability. *Food Res. Int.* **169**, 112853, https://doi.org/10.1016/j.foodres.2023.112853 (2023).
53. Reddy, M. B. & Love, M. in *Impact of Processing on Food Safety* (eds Lauren S. Jackson, Mark G. Knize, & Jeffrey N. Morgan) 99-106 (Springer US, 1999).
54. Rousseau, S., Kyomugasho, C., Celus, M., Hendrickx, M. E. G. & Grauwet, T. Barriers impairing mineral bioaccessibility and bioavailability in plant-based foods and the perspectives for food processing. *Crit. Rev. Food Sci. Nutr.* **60**, 826–843, https://doi.org/10.1080/10408398.2018.1552243 (2020).
55. Wolfe, R. R., Cifelli, A. M., Kostas, G. & Kim, I.-Y. Optimizing protein intake in adults: interpretation and application of the recommended dietary allowance compared with the acceptable macronutrient distribution range. *Adv. Nutr.* **8**, 266–275, https://doi.org/10.3945/an.116.013821 (2017).
56. Aranceta, J. & Pérez-Rodrigo, C. Recommended dietary reference intakes, nutritional goals and dietary guidelines for fat and fatty acids: a systematic review. *Br. J. Nutr.* **107**, S8–S22, https://doi.org/10.1017/S0007114512001444 (2012).
57. USDA. Table of Nutrient Retention Factors. (U.S. Department of Agriculture, Beltsville, Maryland, USA, 2007).
58. Smetana, S., Mathys, A., Knoch, A. & Heinz, V. Meat alternatives: life cycle assessment of most known meat substitutes. *Int. J. Life Cycle Assess.* **20**, 1254–1267, https://doi.org/10.1007/s11367-015-0931-6 (2015).
59. Dettling, J., Tu, Q., Faist, M., Del Duce, A. & Mandlebaum, S. A comparative Life Cycle Assessment of plant-based foods and meat foods. (Quantis USA for MorningStar Farms, Boston, USA, 2016).
60. Saarinen, M., Fogelholm, M., Tahvonen, R. & Kurppa, S. Taking nutrition into account within the life cycle assessment of food products. *J. Clean. Prod.* **149**, 828–844, https://doi.org/10.1016/j.jclepro.2017.02.062 (2017).
61. Sonesson, U., Davis, J., Hallström, E. & Woodhouse, A. Dietary-dependent nutrient quality indexes as a complementary functional unit in LCA: A feasible option? *J. Clean. Prod.* **211**, 620–627, https://doi.org/10.1016/j.jclepro.2018.11.171 (2019).
62. Green, A., Nemecek, T., Smetana, S. & Mathys, A. Reconciling regionally-explicit nutritional needs with environmental protection by means of nutritional life cycle assessment. *J. Clean. Prod.* **312**, 127696, https://doi.org/10.1016/j.jclepro.2021.127696 (2021).
63. Reguant-Closa, A., Pedolin, D., Herrmann, M. & Nemecek, T. Review of diet quality indices that can be applied to the environmental assessment of foods and diets. *Curr. Nutr. Rep.* **13**, 351–362, https://doi.org/10.1007/s13668-024-00540-0 (2024).
64. BLV. Jodstatus in der Schweizer Bevölkerung. (Bundesamt für Lebensmittelsicherheit und Veterinärwesen, Bern, 2019).
65. Fischer, L., Andersson, M., Braegger, C., Herter-Aeberli, I. & Swiss Iodine Study, C. Iodine intake in the Swiss population 100 years after the introduction of iodised salt: a cross-sectional national study in children and pregnant women. *Eur. J. Nutr.* **63**, 573–587, https://doi.org/10.1007/s00394-023-03287-6 (2024).
66. Douziech, M. et al. Recommended impact assessment method within Swiss Agricultural Life Cycle Assessment (SALCA): v2.01. *Agroscope Sci.* **183**, 1–25, https://doi.org/10.34776/as183e (2024).
67. Proviande. Der Fleischmarkt im Überblick 2021. (Proviande Genossenschaft, Bern, 2021).
68. SBV. Milchstatistik der Schweiz 2021. (Schweizer Bauernverband, 2022).
69. Nemecek, T. et al. Swiss Agricultural Life Cycle Assessment: a method to assess the emissions and environmental impacts of agricultural systems and products. *Int J Life Cycle Assessment* (2023). https://doi.org/10.1007/s11367-023-02255-w.
70. SBV. Statistische Erhebungen und Schätzungen über Landwirtschaft und Ernährung. 242 (Schweizerischer Bauernverband, Brugg, 2023).

71. Beretta, C. & Hellweg, S. Lebensmittelverluste in der Schweiz: Umweltbelastung und Vermeidungspotenzial. Wissenschaftlicher Schlussbericht. (ETH Zurich, 2019).
72. Goss, M. A. & Sherwood, J. An absolute environmental sustainability assessment of food. *Food Front.* **5**, 855–866, https://doi.org/10.1002/fft2.371 (2024).

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