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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Product-group-specific nutrient index as a nutritional functional unit for the Life Cycle Assessment of protein-rich foods

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Abstract

Purpose Substitution of animal-source foods with plant-based alternatives requires product-specific information from both the environmental and nutritional perspectives. The use of nutrient indices as nutritional functional units (nFUs) in Life Cycle Assessment (LCA) of food products has been developed to integrate nutritional aspects into the method (nLCA). However, the methodological approaches vary because the execution of LCA always depends on context.

Methods We present a methodological approach for the nLCA of protein-rich foods with a product-group-specific nFU, as update to earlier development work. We compared three strategies for selecting nutrients to be included in the nFU index for protein-rich foods in a national context, considering Finnish nutrition recommendations to different age groups, and the population's dietary habits and nutrient intake. nFUs were demonstrated through cradle-to-plate LCA for foods made with beef, pork, broiler, trout, perch, chickpea, soya mince, and pulled oats as the main ingredients.

Results The selected strategies to format the nFU have a marked impact on the results especially for fish- and plant-based food. The results of each population group, especially children, also differ. The choice of nutrients in the index, the type of food assessed, and the system boundaries of assessment have a considerable impact on the results.

Conclusion The baseline nFU introduced in the study is valuable in producing sustainability information to support the aspiration to a sustainable dietary shift. The index used as the nFU should be formatted based on the study goal and scope, and vulnerable groups must be considered when interpreting the results.

Keywords nLCA · Nutrient index · Protein-rich foods · Functional unit · Sustainable nutrition

1 Introduction

Food production and consumption greatly contribute to environmental changes (Campbell et al. 2017). Food consumption also has extensive health effects. It has been estimated that improvements in diet quality could prevent one out of every five deaths from noncommunicable diseases worldwide (Afshin et al. 2019) and decrease the vulnerability to infections and shortens the duration of infections. Both reducing and preventing environmental impacts and improving nutrition to prevent adverse health effects are key global sustainability goals (UN 2022). When seeking ways to improve the sustainability of our diets and food systems, the integration of nutritional and environmental factors is therefore especially crucial.

Regarding the Western diet, a shift towards more plant-based diets has been identified as one of the most important means to achieve sustainability and health goals (Willett et al. 2019). Although the overall goal is related to the quality of the diet, the required changes are realised in food product choices, because the diet is composed by the chosen product in practice (Saarinen et al. 2017). Sustainable product choices need to be supported by relevant information that integrates environmental and nutritional aspects, considering nutrition at a whole diet level. Methodologically, this can be achieved by integrating the estimation of the

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nutritional quality of the food into Life Cycle Assessments (LCA) of foods (McLaren et al. 2021).

LCA is a relative approach to assess environmental impacts by quantifying the environmental impacts arising from the production–consumption chain of a product and by-products. In this approach, products' functionality is a key concept, especially when products from different value chains are compared (ISO 14040; 14,044). In LCAs, functionality should be presented in the functional unit (FU), which also acts as a reference basis in product comparisons. Usually not considered in LCA studies, the most fundamental reason for consuming food is to ensure an adequate intake of energy and nutrients to maintain bodily functions and health. The daily diet should provide adequate amounts of dietary energy and protein, essential fatty acids, carbohydrates, and micronutrients to support metabolic functions and well-being at all ages.

Sources of dietary proteins are especially interesting because animal-origin foods are typically rich in many important nutrients such as proteins and micronutrients, e.g. vitamin B12. While shifting to more plant-based diets has sustainability benefits, it may also pose some nutritional risks compared with omnivorous mixed diets, especially in vulnerable population groups, if not planned and addressed carefully. In a global modelling analysis, where 25–100% of animal-source foods were replaced with plant-based foods, it was found that in high- and middle-income countries, the baseline low level of vitamin A, folate, iron, potassium, and fibre intakes increased (Springmann et al. 2018). However, calcium, pantothenate (B5), and vitamin B12 intakes decreased to less than recommended when meat was fully substituted. In a randomised controlled trial with healthy adults, partial but substantial replacement of animal-source proteins with plant-source proteins resulted in lower intakes of protein (Päivärinta et al. 2020), iodine, vitamin B12, zinc (Pellinen et al. 2022), vitamin D, and calcium (Itkonen et al. 2021), which was also reflected in the status of the micronutrients measured in the blood and urine. However, the intakes of folate and iron were higher in the plant-based than in the animal-based diet (Pellinen et al. 2022). In a replacement scenario study by Saarinen et al. (2019), selenium also seemed to be among the critical nutrients when meat intake was decreased. Population studies have also shown lower intakes and/or status of vitamin B-12, vitamin D, iodine, zinc, calcium, and selenium among vegetarians and vegans compared to their omnivorous peers (Davey et al. 2003; Elorinne et al. 2016).

These nutritional aspects as functions of foods have been largely ignored in food LCA, as mass-based FUs have been commonly used as a reference for product assessments and comparison between products (Saarinen et al. 2017). Recently, this issue has been addressed in the FAO's report on integrating environment and nutrition into the LCA of food items, with general recommendations for conducting a nutritional LCA (nLCA) (McLaren et al. 2021). The most widely used method to integrate various nutrients into the FU is based on nutrient indices (Green et al. 2021; McLaren et al. 2021) that indicate the nutrient density of food in relation to its quantity or energy content. Although the nutrition indices operate at product level, they take the whole diet approach because they are calculated based on the nutrient concentration of food in relation to the recommended daily intake of nutrients (Drewnowski and Fulgoni 2008). The indices can include nutrients to encourage and nutrients to limit, or combinations of both. As a nutritional measure, they often include both, but the combination indices can lead to negative values, which makes their implementation as an FU impossible (Saarinen et al. 2017; McLaren et al. 2021). Using an index based on nutrients to encourage as the FU and assessing nutrients to limit separately as an impact category have therefore been proposed (Saarinen et al. 2017; McLaren et al. 2021).

However, open methodological issues remain in terms of nutrient indices used as an nFU (McLaren et al. 2021). The main ones include whether the same index should be applied to all food products, or whether a product-group-specific approach should be adopted, in which contexts, and how. McLaren et al. (2021) and Scarborough et al. (2010) proposed using a product-group-specific nutrient index in the FU when comparing substitute products within a food group. Applying the product-group-specific approach, the Finnish Nutrient index (FNIprot) was introduced as an nFU for protein-rich foods by Saarinen et al. (2017), building on the nutrient index called Nutrient Rich Food index NR9 used in nutrition education (Fulgoni et al. 2009). The study showed that general indices such as NR indices and product-group-specific indices provide different results for the LCA when they are used as the FU. The development of relevant product grouping and consequent indices has therefore been identified as one of the major areas for development in nLCA (Saarinen et al. 2017; McLaren et al. 2021).

Furthermore, the FAO's nLCA guidelines (McLaren et al. 2021) suggest the application of the nutrient recommendations of the target population in forming nutrient indices. However, the guidelines do not address how to deal with the fact that different age groups and sexes have their own nutrient recommendations, even within specific nutritional guidelines. Moreover, should special attention be paid to vulnerable population groups with a risk of inadequate nutrient intake? For example, small children need adequate amounts of energy and nutrients to ensure normal growth and development.

In this paper, we further develop the product-group-specific approach of using nutrient indices in the FU by Saarinen et al. (2017) and provide a solid procedure to follow the approach. We demonstrate the development with test calculations for a range of protein-rich foods, which is a key product group for the sustainable food transition. The scope of the method is to provide information to consumers to help their decision-making between products that play analogous roles in a meal and diet, and that could be used as a background information for criteria-based labelling, for example. Special attention is paid to the following issues: (i) how to select nutrients for the nutrient index use as an nFU; (ii) how the sexes and different age groups should be considered in using the nutrient index as an nFU; (iii) how the selection of nutrients in the index affects the LCA results; and (iv) sensitivities related to nLCA. An updated version of FNIprot index and its application for a range of protein-rich foods is also introduced.

2 Materials and methods

In this study, we formatted three different nFUs for protein-rich foods, based on different justifications. The indices were calculated to cover the whole population, i.e. separately for each population group. Demonstrative test LCAs were implemented to evaluate the impact of methodological choices.

2.1 Food grouping and foods in a test calculation

The grouping of foods is a key stage for product-group-specific nFUs; it must ensure reasonable comparison of foods in the context of a specific LCA study. Because this study's approach is to compare protein-rich foods that can replaced each other in a meal, i.e. consumed similarly, the grouping was based on the plate model presented in the Finnish national meal recommendations (VRN 2014). The plate model includes a protein source as part of a meal, e.g. fish, meat, eggs, legumes, nuts, or seeds.

In the demonstrative test calculation, the climate impacts and nutrient indices were determined for complex foods, i.e. foods containing multiple ingredients (McLaren et al. 2021) that are consumed as protein sources and are in an edible form. The studied foods were home-cooked patties and balls made with beef, pork, broiler, trout, perch, chickpea, soya mince, or pulled oats (a protein-rich meat substitute containing oats, peas, and faba beans) as the main ingredients. The recipes were collected from several websites and are presented in detail in the supplementary material (Table S1). The recipes for plant-based foods did not include any ingredients of animal origin. Ingredients given in pieces (e.g. eggs) in recipes were converted to grams, and to calculate the indices, the share of peels and shells was subtracted from the recipes based on Finnish food measures (Sääksjärvi and Reinivuo 2004).

2.2 Calculation of product-group-specific nutrient indices

The nutrient indices were calculated following the same formula used in previous studies (e.g. Fulgoni et al. 2009):

$$\text{Index} = \sum \frac{NUTRIENTi}{DRIi \text{ or } DAi} \times 100/\text{number of nutrients in the index},$$

where $nutrient_i$ is the amount of a selected nutrient in 100 g of a product, DRI_i is a recommendation for the daily intake of $nutrient_i$ when a nutrient is essential for human bodily functions, and DA_i daily allowance of $nutrient_i$ when a nutrient is detrimental to human health when regularly consumed in excess and should therefore be limited. The selection of nutrients for indices that are used as the FU is described in the "Selection of nutrients for the nutrient indices" section. The index that assesses the nutrients that should be limited (LIM index) included saturated fatty acids (SAFA) and sodium (Na).

In the interpretation of the index score, the higher the result of the nutritional index, the more the product contains nutrients selected for the index in relation to the recommended intake—so a higher result is better than a lower result for nutrients to encourage nutrients, and vice versa for nutrients to limit. The contribution (%) of each nutrient to the final nFU index score was calculated to identify which nutrients had the greatest impact on the score.

Nutrient indices are typically produced based on nutritional recommendations for the adult population. However, we wanted to address how considering the nutrition needs of vulnerable groups affect the results. We therefore calculated the nutrient index scores for different sexes and age groups, which have their own nutrient intake recommendations in Finnish nutrition recommendations (VRN 2014). The groups were men and women aged 10–13, 14–17, 18–30, 31–60, 61–74, and over 75, and children aged 12–23 months, 2–5, and 6–9 years. The recommended intakes of nutrients for different sexes and age groups are presented in the supplementary material (Table S2). To calculate the protein intake recommendation in grams, originally based on percentage of energy intake (E%) in the Finnish nutrition recommendations (VRN 2014), protein energy was set to 4 kcal/g. The recommended daily energy intakes were based on Finnish nutrition recommendations for the sedentary population (VRN 2014), except the recommendation for children aged 12–23 months (Hollis et al. 2020) and ≥ 75-year-olds. The recommended energy intakes for ≥ 75-year-olds were set to 1815 and 1887 kcal for women and men respectively based on the given energy intake range in the food recommendations for the elderly (THL 2020). For comparison, we also calculated the indices using EU reference values, which are utilised in nutrition declarations of food packages sold in the EU. These values represent the daily nutrient intakes of an average adult (EU Commission and Parliament 2011).

The nutrient content of the foods (Table S3) was assessed using data for each ingredient from the National Food Composition Database in Finland (THL 2019) and by weighting the nutrient contents of each ingredient with the amounts given in the recipes. Cooking losses in product mass were as follows: beef 18%, pork 21%, broiler 26%, trout 18%, perch 22%, chickpea 20%, pulled oats 14%, soy 17% (Sääksjärvi and Reinivuo 2004).

Cooking losses were also considered in the nutrient contents. The reduced amount of folate, niacin, riboflavin, thiamine, and vitamin B12 was evaluated for the whole products by using nutrient-specific loss factors. The factor was composed by calculating the average loss of the vitamins in minced broiler meet and egg based on the information available in the Food Composition Database in Finland for raw and cooked (without added fat or salt) ingredients, resulting to cooking loss of 13% for folate, 18% for niacin, 5% for riboflavin, 21% for thiamine, and 17% for vitamin B12. According to this approach, there were no losses in mineral nutrients or in vitamins B6 and D.

As stated in Saarinen et al. (2017) and McLaren et al. (2021), it is irrelevant for the LCA result whether the index is calculated for 100 g or 100 kcal, and 100 g was therefore also used in this study. No further weighting or capping was done for the nutrients included in the index due to the lack of a commonly accepted procedure (McLaren et al. 2021). Also, no further validation process for the indices was carried out in this study.

2.3 Selection of nutrients for the nutrient indices

The selection of nutrients was based on a nutrient intake in the current diet of the Finnish adult population according to the National FinDiet Survey (Valsta et al. 2018; Kaartinen et al. 2020). We adapted three different strategies for the selection of nutrients and thus formed three different indices. However, because the food group of protein rich foods was the one under study, the provision of protein was included in each index by default. For the **baseline nutrient index**, we identified the nutrients provided by the typical sources of protein at a significant level in the diets of Finnish adults to capture the impacts of substituting the foods currently consumed as sources of protein. Specifically, the inclusion criterion was that meat, eggs and/or dairy products were the most or second most important source of the nutrient according to the National FinDiet Survey (Valsta et al. 2018; Kaartinen et al. 2020). Based on this, the nutrients included in the baseline nutrient index were protein, calcium (Ca), iron (Fe), selenium (Se), zinc (Zn), vitamin B6, vitamin B12, niacin, riboflavin, and thiamine.

Some nutrients obtained from current protein sources exceed the recommended intakes at the population level while the intake of some is insufficient, and thus, the second nFU index was formatted so that it considers the provision of these critical nutrients. According to this selection strategy, we identified and selected nutrients with low or borderline intake at population level (Kaartinen et al. 2020). It was also required that meat, eggs, and milk were among the most important sources of these nutrients (Kaartinen et al. 2020). For example, currently, only 6% of women and 28% of men in Finland meet the folate recommendation (Valsta et al. 2018). Other such nutrients are Fe and thiamine. In Finland, intakes of iodine (I) and selenium (Se) are frequently monitored due to their low content in foods because of low concentration in the soil (Finnish Food Authority 2021; Valsta et al. 2018). This second selection procedure resulted in the **scarce nutrients index** including protein, Fe, I, Se, folate, and thiamine.

Generally, nutrient indices are formatted based on current food consumption, and thus, if the food consumption of population changes, the indices must change accordingly. Because a shift from animal-based products to more plant-dominant foods is desired for health and environmental reasons (Willett et al. 2019), for the third approach, we focused on the nutrients whose intake would be further reduced in this anticipated dietary shift. Based on the Finnish nutrient intake survey (Valsta et al. 2018) and dietary scenarios (Springmann et al. 2018; Saarinen et al. 2019), the intake of the following nutrients was estimated to possibly reduce with dietary change: protein, Ca, Zn, vitamin B12, vitamin D, and riboflavin. These nutrients were included in the **dietary shift index**.

2.4 Methodological choices in Life Cycle Assessments

The nutrient indices are used directly as nFUs, i.e. the environmental impacts are divided by the index scores. In the interpretation of the result, a greater environmental impact result is worse than a smaller result (as typical in LCA) in contrast with the interpretation of the nutrient indices. Because the index score is calculated for 100 g of cooked food product, the environmental impact was also first calculated for 100 g of cooked food product, and these results are compared with the results produced using nutrient indices as the nFU.

In LCA, the processes of a product system included in the assessment are defined by the system boundary (ISO 2006). In this study, the complex foods were assessed from cradle to plate, including emissions from primary production, post-farm processing of the raw materials, packaging, transport to a regional distribution centre and retail of the raw materials, and energy consumption of the cooking phase at home. A detailed description of the recipes and data sources is presented in the supplementary material (Table S1). Same cooking losses in product mass were used in LCA than in the calculation of nutrient contents of foods.

The implementation of the nFUs was demonstrated through assessing climate impacts of the studied products. The LCA was made using SimaPro 9.3 software and characterisation factors from the IPCC fifth assessment report (IPCC 2013). For ingredients, Agri-footprint 5 (NL, economic allocation) data were used, with a few exceptions (Durlinger et al. 2014). Data concerning trout farmed in Norway and perch caught by gillnet in Finland were obtained from Silvenius et al. (2022). The climate impact of pulled oats and oat cream was reported by the companies (Gold & Green Foods Ltd. 2022; Oatly 2022). The climate impact of soy sauce was derived from CarbonCloud (2022). Due to the lack of data on herbs and spices, salt (ecoinvent, Wernet et al. 2016) was used as a proxy for all dry spices, and spinach as a proxy for fresh herbs. Onion was also used as a proxy for garlic, and wheat flour as a proxy for breadcrumbs.

Data concerning emissions associated with packaging, transport to a distribution centre, and retail were derived from Clune et al. (2017). The energy consumption of cooking by frying on a pan was derived from Frankowska et al. (2020). To unify the energy consumption between recipes, the energy consumption was adjusted to 1 kg of raw products. A cooking time of 15 min was assumed in all recipes, resulting in the energy consumption of frying being 0.54 kWh/kg for raw products and baking in the oven consuming 0.76 kWh/kg. Emissions of the energy consumption were modelled using data concerning the electricity mix of Finland (Agri-footprint, Durlinger et al. 2014). The exact names of the processes used in the LCA are listed in the supplementary material (Table S1).

2.5 Sensitivity

To test how changes in the ingredients of the recipes affected baseline nutrient indices and the climate impacts of the complex foods, richer, perhaps more festive, “gourmet” versions, including dairy products in the recipe, were assessed. Recipes for gourmet versions were obtained from several websites and fully presented in the supplementary material (Table S4 and S5). The indices and the climate impacts were calculated in the same way as for the initial recipes, the same percentage of cooking losses in mass and nutrient contents were used as in the original recipes. The energy consumption of cooking in an oven was derived from Frankowska et al. (2020).

To test the effect of system boundaries of the assessment, the main ingredients were assessed separately as raw and cooked simple foods. The results were calculated for the baseline nutrient index using population weighted average of all population groups (population in 2022, OSF 2023), and the relative differences in results were compared to everyday versions of cooked complex foods. The assessment was carried out similarly to the assessment of complex foods, except for dry soya mince 2.62-fold change in mass due absorption of water in the cooking phase was assumed, based on the National Food Composition Database (THL 2019).

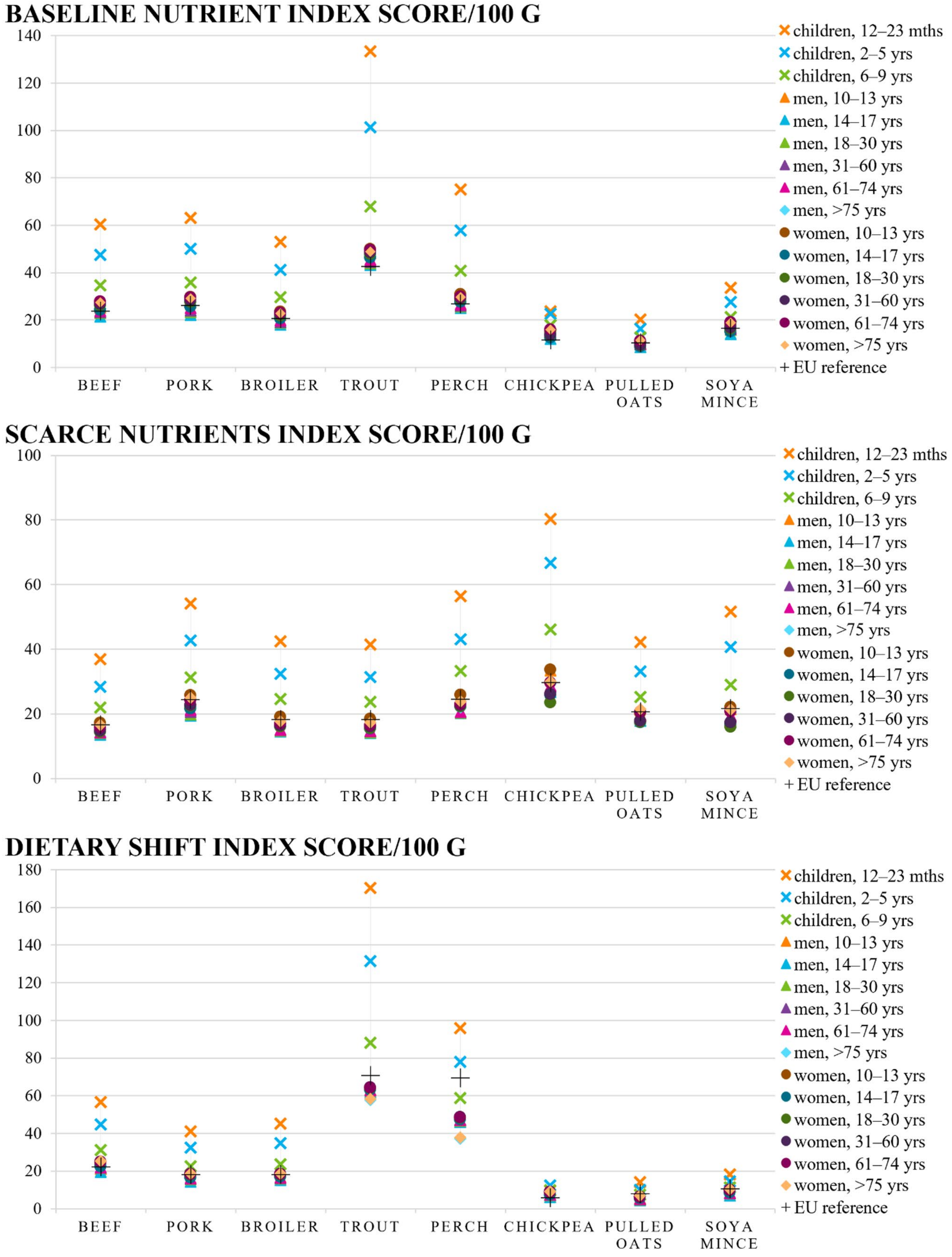
In addition to nutrient content, the nutritional quality of food is affected by the bioavailability of the nutrients. Especially in plant-based foods, antinutrients such as phytates and certain polyphenols, as well as dietary fibre, may bind minerals and vitamins and thus hinder their absorption (Melse-Boonstra 2020). Currently, there is not enough information to include the bioavailability extensively in nutrient indices. We therefore conducted a sensitivity analysis of the effect of including iron absorption in the results. We used a factor of four times higher absorption of heme iron than iron from plant foods. The factor is based on heme iron contributing 10% to the intake, but 40% to the iron status measured from blood. The factor used here is a rough estimate. Many factors affect iron absorption, including phytic acid and polyphenols as inhibitors and vitamin C and muscle tissue as factors that enhance iron absorption (Lynch et al. 2018).

3 Results

3.1 Nutrient index calculations

The index scores indicating the nutrient density (in relation to product quantity) of foods varied considerably between both recipes and indices (Fig. 1 and Table S6). The contribution (%) of each nutrient to the final index scores also varied considerably between the recipes and indices (Table 1). Furthermore, the scores of the youngest children were considerably higher than those for the adult population across the recipes and indices (Fig. 1). In turn, the difference between the working-age and elderly populations was small.

Patties and balls with fish as the main ingredient had the highest nutrient index scores of recipes when using the **baseline nutrient index** (Fig. 1). Recipes with plant-based main ingredients had the lowest nutrient index scores. In fish recipes, vitamin B12 contributed an exceptional amount to the nutrient index scores (Table 1), while in plant-based recipes, B12 did not contribute anything, because plant-based ingredients do not contain vitamin B12 (Table 1). The contribution of different nutrients was most evenly distributed in the beef- and soya bean–based recipes, with the contribution of all five nutrients together more than 10%, while at the other extreme, it was only 2 or 3% for fish recipes, depending on the fish variety. Perhaps unsurprisingly, protein contributed less than 10% to the baseline nutrient index score of all recipes other than those with pulled oat and soya mince as the main ingredient. However, calcium contributed least across the recipes. The index score calculated with the EU reference intake was at the same level as the average of the population above 10 years of age, except for trout and chickpea,


BASELINE NUTRIENT INDEX SCORE/100 G
0
20
40
60
80
100
120
140
BEEF
PORK
BROILER
TROUT
PERCH
CHICKPEA
PULLED OATS
SOYA MINCE
children, 12–23 mths
children, 2–5 yrs
children, 6–9 yrs
men, 10–13 yrs
men, 14–17 yrs
men, 18–30 yrs
men, 31–60 yrs
men, 61–74 yrs
men, >75 yrs
women, 10–13 yrs
women, 14–17 yrs
women, 18–30 yrs
women, 31–60 yrs
women, 61–74 yrs
women, >75 yrs
+ EU reference
SCARCE NUTRIENTS INDEX SCORE/100 G
0
20
40
60
80
100
BEEF
PORK
BROILER
TROUT
PERCH
CHICKPEA
PULLED OATS
SOYA MINCE
children, 12–23 mths
children, 2–5 yrs
children, 6–9 yrs
men, 10–13 yrs
men, 14–17 yrs
men, 18–30 yrs
men, 31–60 yrs
men, 61–74 yrs
men, >75 yrs
women, 10–13 yrs
women, 14–17 yrs
women, 18–30 yrs
women, 31–60 yrs
women, 61–74 yrs
women, >75 yrs
+ EU reference
DIETARY SHIFT INDEX SCORE/100 G
0
20
40
60
80
100
120
140
160
180
BEEF
PORK
BROILER
TROUT
PERCH
CHICKPEA
PULLED OATS
SOYA MINCE
children, 12–23 mths
children, 2–5 yrs
children, 6–9 yrs
men, 10–13 yrs
men, 14–17 yrs
men, 18–30 yrs
men, 31–60 yrs
men, 61–74 yrs
men, >75 yrs
women, 10–13 yrs
women, 14–17 yrs
women, 18–30 yrs
women, 31–60 yrs
women, 61–74 yrs
women, >75 yrs
+ EU reference

◂**Fig. 1** The **baseline nutrient index**, the **scarce nutrient index**, and the **dietary shift index** score of patties and balls. The higher the result of the nutritional index, the more the product contains nutrients selected for the index in relation to the recommended intake

whose scores were lower. However, the index scores were lower than the index scores calculated for younger children across the recipes.

When using the **scarce nutrient index**, chickpea balls had the highest score, with the rest of the recipes at the same level (Fig. 1). In this index, different nutrients contributed more evenly to the score than in the baseline nutrient index (Table 1). For the scarce nutrient index, the contribution of individual nutrients within one product varied at most between 3 and 40% (perch patties), while for the **baseline nutrient index**, the contribution ranged at most between 1 and 54% (trout patties). In general, the scores of the scarce nutrient index across the recipes were lower than those of other nutrient indices. Plant-based foods scored higher on this index than the other indices, due to high iron and folate content. The index score calculated with the EU reference intake was 3 to 14% higher than the average of the population over 10 years of age, but lower for younger children.

Compared to the baseline nutrient index, the **dietary shift index** resulted in an increase in the index scores for trout and perch, while the indices for other foods decreased (Fig. 1). In general, the dietary shift index led to the highest scores, but the relative differences between foods were similar to the baseline nutrient index. The contribution of vitamin B12 to these index scores was even stronger than to the baseline nutrient index, but the contribution of different nutrients within one product was in any case more extreme due to the smaller amount of nutrients in the index (Table 1). The index score calculated with the EU reference intake was lower than the average of the population over 10 years of age for beef and chickpea and higher for other foods, especially for perch (67% higher). Using the EU reference intake resulted in lower scores than the index calculated for younger age groups in other foods than perch patties in the 6–9 age group.

3.2 Climate impact of foods

The climate impact (kg CO_2 eq./100 g) of beef patties was considerably higher than that of other assessed products (Fig. 2). Regarding products other than beef, the climate impact of plant- and wild-fish-based products was lower than that of pork-, broiler-, or farmed-trout-based products.

The climate impact follows the index scores inversely, meaning that the high index scores for children lead to the lowest climate impacts (Fig. 3 and Table S7). The climate impact per nutrient index varied depending on the index used, the scarce nutrient index leading to notably higher impacts than the baseline or the dietary shift index (Fig. 3 and Table S7). Using the nutrient index instead of the mass-based FU, the difference in climate impact between animal-source foods and plant-based foods generally decreased. Even then, the climate impact of beef was the highest, affected by a notably higher climate impact per 100 g and the average nutrient index score compared to other foods. The relative difference between the beef-based and other recipes narrowed when the baseline nutrient index and the dietary shift index were used but widened when using the scarce nutrient index. The high nutrient index scores and relatively low climate impact of fish foods therefore led to the low climate impacts per nutrient index.

3.3 Nutrients to limit

The LIM indices indicated the levels of nutrients to limit in patties and balls: the higher the LIM index, the higher the level of SAFA and/or sodium in the food (Table 2). Beef balls high in SAFA received the highest LIM index for several age groups (both sexes), while pulled oats and chickpea balls also scored quite highly due to the relatively large amount of NaCl in the recipe compared to other products (Table S3). In pulled oats and chickpea, the LIM index for children aged 1–9 years was especially high because of the strict recommended maximum NaCl intake (Table S2). According to the recipe, trout patties that were prepared without added salt were scored with the lowest LIM index, followed by the broiler-based recipe.

3.4 Sensitivity

The sensitivity analysis showed that changing ingredients and ratios of ingredients of the recipe also influenced the results (Table 3 and Table S8). Especially for fish, including dairy products to recipes (in the gourmet recipe) led to an increase of the climate impact per 100 g, while the baseline nutrient index score reduced, resulting in an increase in the climate impact per unit of the nutrient index score (+21%, +24%). Instead, for plant-based foods, except for soya mince, the inclusion of dairy products in the recipes increased both the nutrient index scores and the climate impact per 100 g. For soya mince, adding an ingredient basis to the gourmet recipes compared to the original recipe led to an increase in the nutrient index score but a minimal change in the climate impact per 100 g. In general, the assessment of single ingredients led to larger differences in results between foods than the comparison of complex foods (Table 3 and Table S8). This is because all the recipes included similar ingredients, which equalised the differences of the main ingredients.

Meat-based foods had the highest LIM indices among the gourmet patties and balls, indicating that the dairy products that were used to prepare the products contributed especially

Table 1 Contribution (%) of each nutrient to the nutrient index score

Baseline nutrient index	Beef	Pork	Broiler	Trout	Perch	Chickpea	Pulled oats	Soya mince
Protein	8%	7%	9%	5%	8%	7%	23%	11%
Ca	1%	1%	1%	3%	4%	7%	3%	6%
Zn	18%	9%	8%	2%	4%	14%	8%	11%
Vitamin B12	24%	12%	22%	54%	35%	0%	0%	0%
Riboflavin	3%	7%	8%	2%	3%	4%	3%	5%
Fe	6%	4%	3%	1%	2%	29%	34%	23%
Se	12%	11%	18%	7%	19%	8%	4%	4%
Vitamin B6	10%	9%	8%	8%	6%	11%	7%	11%
Niacin	16%	18%	20%	17%	17%	10%	7%	17%
Thiamine	2%	21%	4%	2%	2%	9%	12%	12%
Scarce nutrients index	**Beef**	**Pork**	**Broiler**	**Trout**	**Perch**	**Chickpea**	**Pulled oats**	**Soya mince**
Protein	21%	14%	19%	23%	17%	5%	20%	15%
Fe	15%	7%	6%	7%	3%	23%	29%	33%
Se	32%	22%	38%	33%	41%	6%	4%	5%
I	20%	14%	21%	19%	31%	18%	33%	2%
Folate	5%	2%	7%	7%	3%	41%	5%	29%
Thiamine	7%	41%	9%	10%	5%	7%	10%	16%
Dietary shift index	**Beef**	**Pork**	**Broiler**	**Trout**	**Perch**	**Chickpea**	**Pulled oats**	**Soya mince**
Protein	14%	18%	18%	6%	8%	20%	63%	34%
Ca	2%	2%	2%	4%	5%	23%	7%	17%
Zn	33%	24%	16%	2%	4%	43%	22%	34%
Vitamin B12	44%	32%	44%	67%	37%	0%	0%	0%
Vitamin D	2%	4%	4%	19%	43%	0%	0%	0%
Riboflavin	6%	19%	15%	2%	3%	14%	7%	15%

to the SAFA levels, even more than meat. In general, SAFA levels at least doubled in the gourmet versions compared to the original versions. Added salt increased the LIM index of gourmet trout patties compared to the original version. The sodium level was also higher in gourmet broiler patties compared to the original version of the patties. Otherwise, the sodium level was similar in gourmet and original versions of the patties and balls.

Considering the lower absorption of iron from plant-based foods resulted in 16–25% lower indices for chickpea, pulled oats, and soya mince (Table 4). The climate impacts therefore increased.

4 Discussion

Using nutrient indices as the FU follows the principles of LCA, answering the “what”, “how much”, “how well”, and “how long” aspects of the FU given in the PEFCR guidance (European Commission 2018). In this study, we formulated three nFUs with slightly different answers to “what”. The rest of the three aspects are covered in the index calculation in the form of the nutrient content of foods and the daily reference intake.

4.1 Nutrient selection strategies

The **baseline nutrient index** included the main nutrients provided by the protein-source foods in the current diet. Considering the context of LCA, this indicates that providing these nutrients is the primary nutritional function of protein-source food. This may ignore some nutrients that are or could be obtained from fish- or plant-based foods to a considerable extent. On the other hand, the other two nutrient indices addressed some of them, for example, Vitamin D. The comparison of three different indices should therefore have ensured that no major misleading conclusions were reached. The **scarce nutrient index** was based on the idea that the function was to provide nutrients that most promoted health in the context of the current public nutrition with the current nutrient intake of the Finnish population (Kaartinen et al. 2020). However, this index produced somewhat similar scores for all foods and therefore did not properly differentiate them. This approach does not consider a possible risk of reduced intake of nutrients that are currently abundantly obtained from typical protein-source foods. Nutrients that were adequately obtained were therefore ignored. The **dietary shift index** emphasises the nutrients whose intake

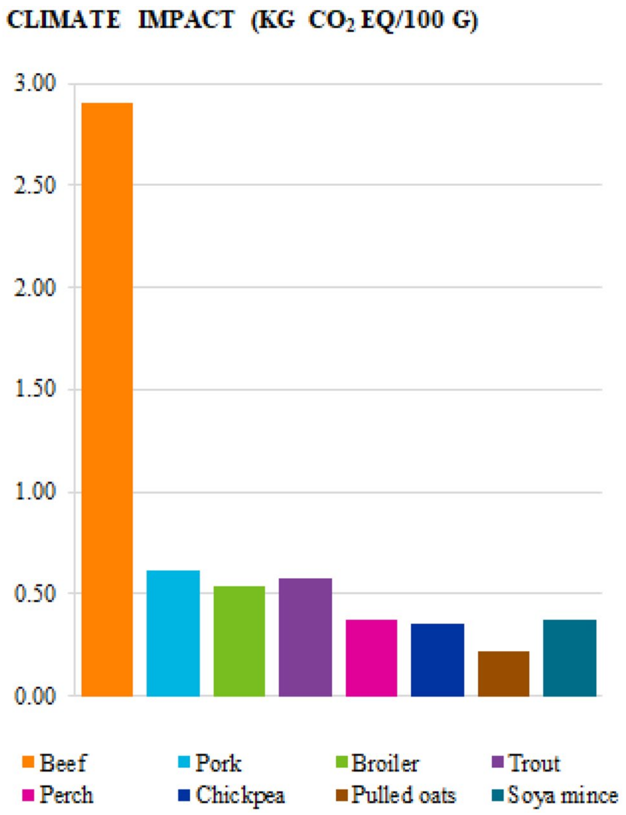


Fig. 2 Climate impact (kg CO_2 eq./100 g) of cooked patties and balls. Note that in the climate impacts, a higher result refers to a greater impact and is thus worse than lower results, which is the opposite of the nutrient index results

was estimated to be reduced in the dietary shift to a more plant-based diet.

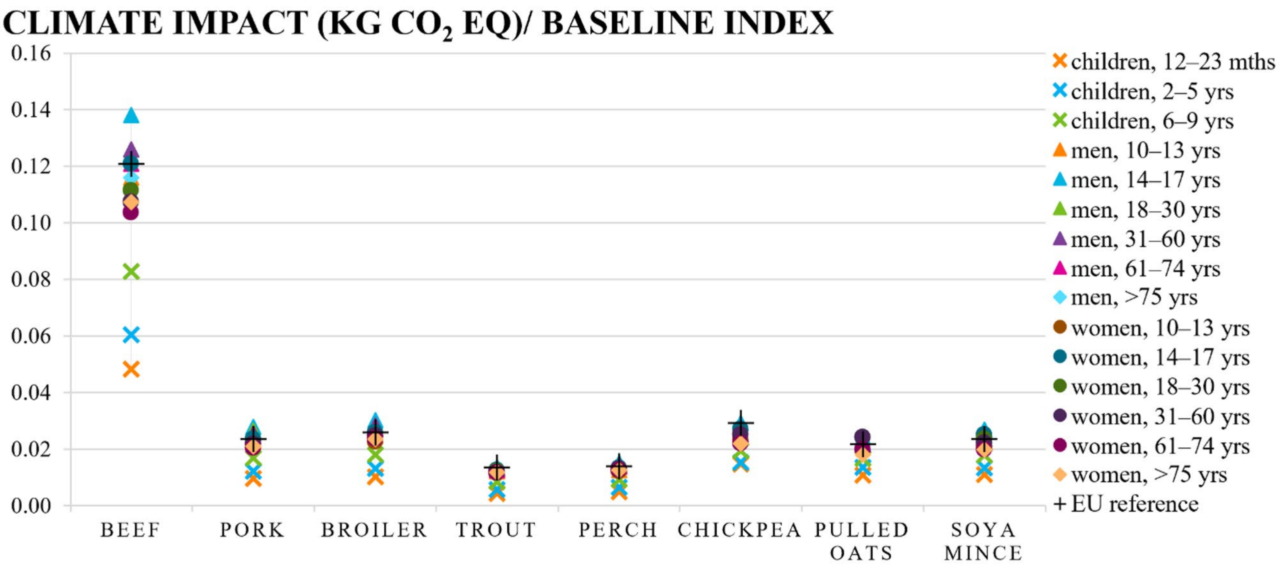
The baseline nutrient index and the dietary shift index produced quite similar results for the protein sources assessed in the test calculations. This is understandable because the selection of nutrients in both was based on a current diet rich in meat (and milk). In the baseline and dietary shift indices, meat-based products scored better than for the scarce nutrient index, which addressed nutrients relatively less abundant than in the current diet. The scarce nutrient index rather highlights products that contain nutrients that should be obtained more, while the **baseline nutrient index** and the **dietary shift index** focus on the maintenance of good nutrient intake from the main protein sources in the current diet. This is to some extent a conservative starting point, but it anchors the need for change in the current situation. Given that food consumption patterns tend to change rather slowly and are typically based on long-established customs rather than sustainability issues (Faria and Kang 2022), this may be justified.

We selected the nutrients for the nutrient indices based on the food consumption and nutrient intake study for the adult population (Kaartinen et al. 2020) and at the same time, considered the product grouping based on the plate model. How well did the selection perform? According to the contribution analysis of the **baseline nutrient index**, all nutrients other than Ca largely contributed to some indices in the test calculation. This means these products are indeed significant sources of these nutrients, and the contribution analysis therefore validates the baseline nutrient index from this perspective. The situation would probably also be the same regarding calcium if a milk-based product had been among the products being tested. The contribution of protein to the total index scores remains relatively low compared to other nutrients, showing that single nutrient nFUs neglect the provision of other relevant nutrients. This highlights the need to include also other nutrients in assessments of protein-source foods.

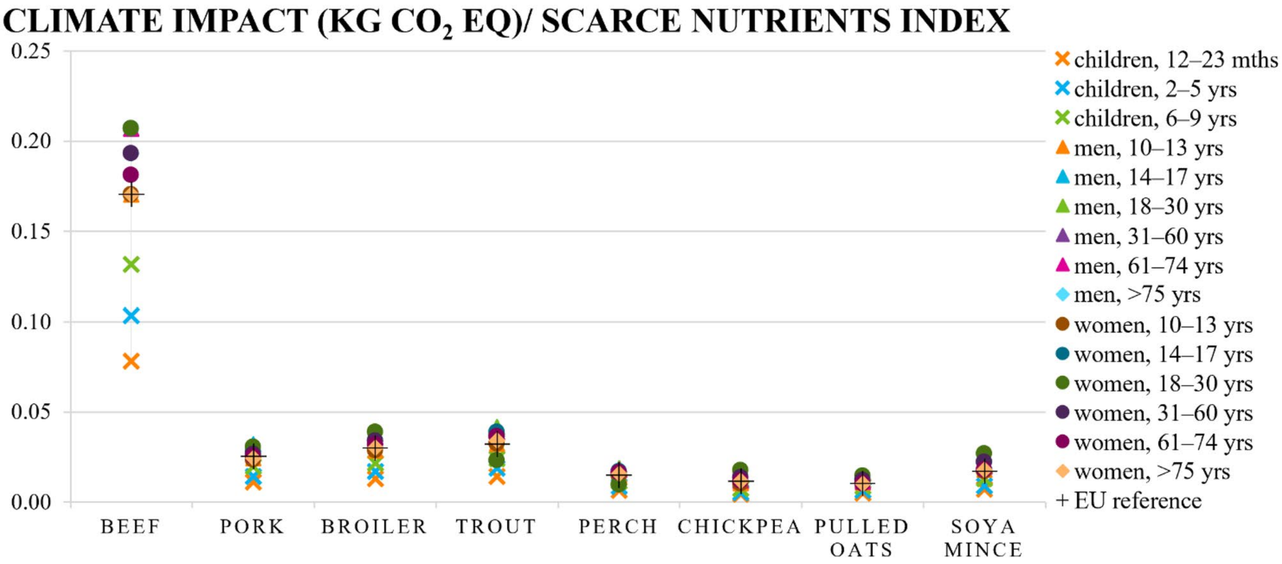
For the other nutrient indices, the contribution analysis reveals that complex foods with many kinds of main ingredient basis can contribute to the intake of scarce nutrients and nutrients that may become scarce in the dietary shift to more plant-based diets. The only significant exception to this is an intake of vitamins B12 and D from plant-based raw materials—plant-based foods do not contain these nutrients unless the foods are supplemented with these nutrients (the consideration of which in the nutrient indices remains controversial). However, uncertainty related particularly to the selection of the dietary shift index is quite high because it is currently unknown exactly which foods future diets will contain and therefore which nutrients will be abundant or scarce. We checked the selected nutrients against the scenarios for the vegan diet and a diet rich in fish and milk (not containing meat) provided by Saarinen et al. (2019) for Finland. These scenarios were designed to meet the nutrient recommendations and are thus not self-selected diets. This check supported the selection of nutrients for the **dietary shift index**, i.e. an intake of the selected nutrients tends to be lower than the others. However, the scenario diets were based on only 92 product groups, representing mainly the raw material basis of diets rather than future complex foods. As this study shows, the selection and ratio of ingredients in foods affect the nutrient index scores.

4.2 Target population

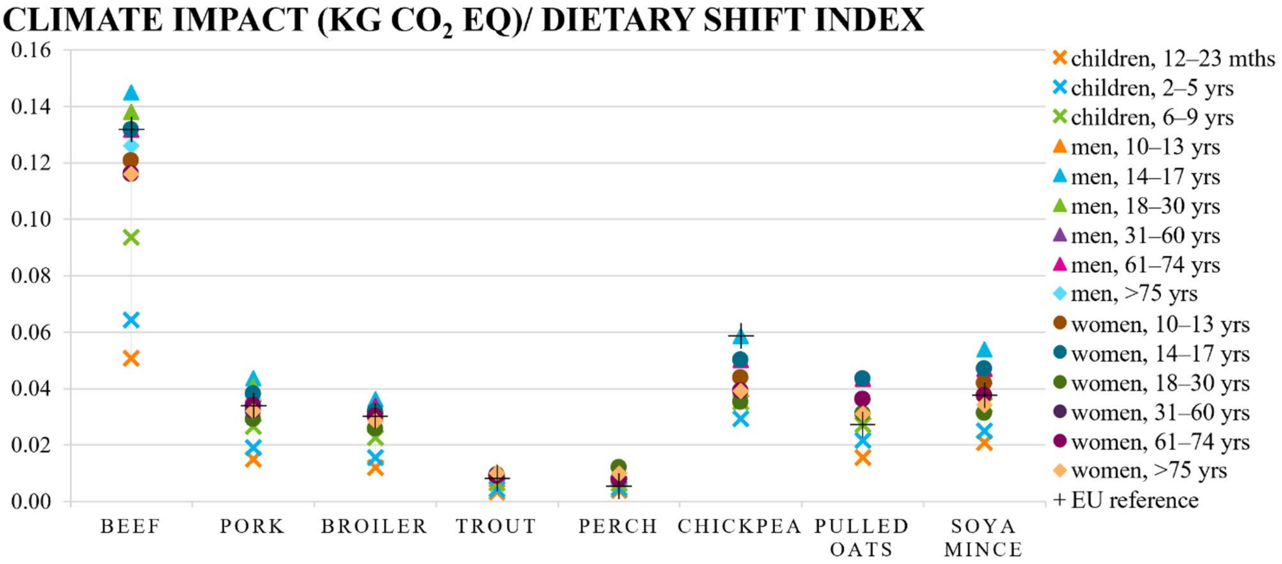
The population group under study should be clearly defined, and the nFU calculated based on the group's nutritional recommendations (McLaren et al. 2021). We considered vulnerable population groups—children, adolescents, and elderly population—to study the impact of their special nutritional needs on the indices. These population groups may be at increased risk of decreasing availability of protein-source foods, as protein and beneficial composition of amino acids are very important for physical and cognitive growth and



CLIMATE IMPACT (KG CO$_2$ EQ)/ BASELINE INDEX



CLIMATE IMPACT (KG CO$_2$ EQ)/ SCARCE NUTRIENTS INDEX



CLIMATE IMPACT (KG CO$_2$ EQ)/ DIETARY SHIFT INDEX

◂**Fig. 3** Climate impact (kg CO_2 eq./index) of patties and balls with the FU of the **baseline nutrient index**, **scarce nutrient index**, and **dietary shift index**. The cross represents the mean, and the line the median of the population groups. Please note that in the climate impacts, a higher result refers to a greater impact and is thus worse than lower results, which is the opposite of the nutrient index results

development. Here, we assessed selection of patties and balls made with different protein sources as the main ingredient. Especially the recipes with meat as main ingredient are typical foods consumed in Finland, and mixtures with similar ingredients are used in different dishes, such as meatballs, patties, and meat loaf. Therefore, studying the substitution impact of these foods in the demonstrative nLCA is reasonable in the Finnish context.

In particular, the results for children differ greatly from the population average and the EU reference. Due to relatively lower nutrient intake recommendations, 100 g of any product naturally contributes to children's nutrition and nutrient index scores more than to adults'. Food portions for children are usually smaller than for adults, and it may therefore be justified to base the calculation of the nutrient index for children on smaller portions, in which case the index scores will be lower. However, when the nutrient index is used as the nFU, the difference disappears because environmental impacts are calculated for the same amount as the nutrient index: the ratio of these two measures is always the same (Saarinen et al. 2017; McLaren et al. 2021). This means that when a nutrient index is used as the FU, the difference between children and adults in the final outcomes of nLCA is real. This implies that the environmental cost (impact) of providing the nutritional service (function) of a product for children is lower than for adults. Test calculations also imply that the environmental impact of beef-based complex food eaten by a child is much lower relatively than that eaten by an adult (when nutritional quality is considered in parallel). This is because these products are rich in nutrients that are particularly valuable for children. The nutritional recommendations for different population groups should therefore be considered in the interpretation and utilisation of results.

Among the dietary shift index scores calculated for adults, the scores based on the EU reference values were relatively high in the case of trout and perch patties, while for the elderly (men and women ≥ 75 years), the scores were low for these products compared to the other adult groups. This is because the reference intake of vitamin D is much lower in the EU regulation (5 µg) compared to Finnish dietary recommendations, especially the recommendation for ≥ 75-year-olds (20 µg) (Table S2). Vitamin D is essential for bone health in the elderly (VRN 2014), and overall in the Nordic countries, special attention needs to be paid to vitamin D intake due to the limited availability of sunlight during the winter months (Kårlund et al. 2022).

4.3 Applying nutrient indices as functional unit

According to the results of the test calculations, the strategy to choose which nutrients are included in the index used in the nFU may lead to very different results (Fig. 1), not to mention the results when a mass-based FU is used (Fig. 2). The **scarce nutrient index** especially differed from others, scoring the plant-based products higher compared to animal-based products. This led to conclusion that the climate impact of plant-based complex foods was lower than meat- and fish-based complex foods. Using the other indices as nFUs suggested that compared to fish-based complex foods, the climate impact of plant-based complex foods was higher, and in pork- and broiler-based complex foods, the climate impact was at the same level. In turn, considering the **dietary shift index** results for children, even the climate impact of beef is at the same level as the plant-based products, when the other nutrient indices are used, it remains clearly higher. This suggests that the climate burden relative to the nutritional benefits of beef-based complex food eaten by a child is at the same level as plant-based complex foods eaten by adults, considered in the context of diets that are much more plant-based than the diets consumed today.

We applied these different nutrient selection strategies to explore and demonstrate how nutrient indices act as the nFU. However, regarding the final applications, the nutrient selection strategy should be in line with the goal and scope of the study, as with any other methodological choices in LCA (McLaren et al. 2021). Because the indices include different selection of nutrients, they have different implications for example to human health. If the goal and scope is to provide a basis for information to help consumers' decision between products in the current situation, the **baseline nutrient index** may be the best choice. However, if the aim is to anticipate the possible future situation, the dietary shift index may be a better option. However, they seem largely to confer the same conclusions. The scarce nutrient index seems most appropriate in situations where a complementary product is sought instead of substitutes, because it does not factor in the maintenance of an adequate intake of nutrients that are typical of current protein sources.

According to the sensitivity analysis, the system should be assessed from cradle to plate, i.e. also considering the cooking losses in mass and nutrient content. This is in line with previous studies (Saarinen et al. 2017) and the proposal by McLaren et al. (2021). Including the cooking phase in the assessment affects the indices in two ways: cooking loss in mass increases the nutrient density of foods; but at the same time, cooking loss in nutrients decreases it.

Table 2 LIM index scores of patties and balls. The darker colour indicates the higher score

		Beef	Pork	Broiler	Trout	Perch	Chickpea	Pulled oats	Soya mince
Children	12–23 mths	54	48	32	15	42	54	57	45
Children	2–5 yrs	38	33	21	10	27	34	36	29
Children	6–9 yrs	32	28	20	8	26	34	36	28
Men	10–13 yrs	21	18	12	6	16	20	21	17
Women	10–13 yrs	22	19	12	6	16	20	21	17
Men	14–17 yrs	19	17	12	5	15	20	21	17
Women	14–17 yrs	21	18	12	6	16	20	21	17
Men	18–30 yrs	19	17	12	5	15	20	21	17
Women	18–30 yrs	21	18	12	6	16	20	21	17
Men	31–60 yrs	19	17	12	5	15	20	21	17
Women	31–60 yrs	22	19	12	6	16	20	21	17
Men	61–74 yrs	21	18	12	6	16	20	21	17
Women	61–74 yrs	23	20	12	6	16	20	21	17
Men	≥75 yrs	23	20	12	7	16	20	21	17
Women	≥75 yrs	24	20	13	7	16	20	21	17
EU reference		21	18	11	6	14	17	18	14

There are therefore increases in the nutrient indices of the main ingredients for which cooking loss in mass occur, i.e. meats, whereas for plant-based main ingredients, there is no loss in mass, and the cooking loss in nutrients therefore results in a decrease in the indices. The inclusion of the cooking phase also contributes to environmental impacts. Applying cradle-to-plate system boundaries is especially important when the comparison includes products that are ready to eat such as pulled oats and products that need to be cooked such as meats. In addition to cooking losses, for some food products, the cooking phase can cause the majority of the total emissions (Frankowska et al. 2020).

Table 3 Results with different recipe content and system boundaries (including the cooking phase) presented as population weighted average **baseline nutrient index** scores, climate impacts per 100 g, climate impact per unit of baseline nutrient index, and LIM indices. Gourmet recipes are more versatile than the original recipes, including, e.g., dairy products, and simple foods are the main ingredient used in the recipes for patties and balls

	Beef	Pork	Broiler	Trout	Perch	Chickpea	Pulled oats	Soya mince
Nutrient index (nutrient index score/100 g)								
Original recipes	27	28	22	50	30	15	10	18
Cooked complex food, gourmet recipes	27	28	25	49	27	18	13	22
Cooked simple food	40	41	32	56	35	11	13	18
Raw simple food	33	35	27	49	29	11	13	53
Climate impact (kg CO_2 eq./100 g)								
Original recipes	2.90	0.61	0.54	0.58	0.38	0.35	0.22	0.38
Cooked complex food, gourmet recipes	2.82	0.67	0.70	0.70	0.45	0.53	0.27	0.38
Cooked simple food	5.38	1.00	0.87	0.69	0.41	0.28	0.29	0.29
Raw simple food	4.01	0.72	0.63	0.49	0.28	0.25	0.26	0.74
Climate impact/nutrient index (kg CO_2 eq./unit of nutrient index)								
Original recipes	0.108	0.022	0.024	0.012	0.013	0.024	0.021	0.021
Cooked complex food, gourmet recipes	0.103	0.024	0.027	0.014	0.016	0.029	0.021	0.017
Cooked simple food	0.135	0.024	0.027	0.012	0.012	0.026	0.023	0.016
Raw simple food	0.121	0.021	0.023	0.010	0.009	0.022	0.020	0.014
LIM index (nutrient index score/100 g)								
Original recipes	22	20	13	6	17	21	23	18
Cooked complex food, gourmet recipes	33	31	37	17	29	15	20	20

4.4 Nutrients to be limited

The low climate impact per nutrient index does not necessarily indicate that the food will be healthy and sustainable, but the concentration of nutrients to limit (LIM index) should also be considered. Including nutrients to limit in the nFU with nutrients to encourage may even lead to a negative index score, which makes it unsuitable to be used as the nFU (Saarinen et al. 2017; McLaren et al. 2021). The LIM index should therefore be used as a separate measure.

According to our results, LIM index scores of different complex foods varied within a quite narrow range, with the exception of trout- and broiler-based foods, and in terms of children. Regarding children, the explanation is the same as in other nutrient indices; 100 g of any product represents a much larger proportion of children's diet than that of adults. In other respects, when interpreting the LIM index results, it is important to note that the recipe greatly affects the LIM index scores. For example, the recipe for the trout balls contained no salt at all, which is strongly reflected in the low

Table 4 Sensitivity of baseline results to lower absorption of iron from plant-based foods. The results represent the weighted average of population groups

Nutrient index (nutrient index score/100 g)				
Index	**Method to include iron**	**Chickpea**	**Pulled oats**	**Soya mince**
Baseline	Original version	15	10	18
Baseline	Bioavailability considered	11	8	14
Scarce nutrients	Original version	36	22	24
Scarce nutrients	Bioavailability considered	31	20	20
Climate impact/nutrient index (kg CO_2 eq./unit of nutrient index)				
Index	**Method to include iron**	**Chickpea**	**Pulled oats**	**Soya mince**
Baseline	Original version	0.024	0.021	0.021
Baseline	Bioavailability considered	0.031	0.028	0.026
Scarce nutrients	Original version	0.011	0.011	0.018
Scarce nutrients	Bioavailability considered	0.014	0.014	0.025

index scores. Furthermore, salt is typically added to complex food in the manufacturing or cooking phase, while saturated fatty acids (SAFA) are often inherently in the food item or ingredient (Valsta et al. 2018). In this study, we chose typical recipes from internet sources, and the amount of added salt or fat was therefore unequal in the recipes. In this sense, our comparison is merely between recipes, not between main ingredients, for example. To our understanding, this reflects reality; people choose recipes among those that are available, perhaps adjusting them according to their taste. Our main intention was to raise the issue of nutrients to limit in complex foods as part of sustainability. In this respect, the LIM index should be calculated based on the actual recipes used in cooking.

4.5 Strengths and limitations

One of the biggest challenges concerning nutrient indices as a presentation of nutritional quality is how to address the bioavailability of nutrients. Insufficient inclusion of bioavailability is also the major limitation of this study. As shown in the sensitivity analyses, considering the bioavailability can have a significant impact on the results. In our study, considering a lower bioavailability of plant-based Fe, the climate impacts of plant-based balls and patties were greater than those of pork and broiler-based products (Fig. 3 and Table 4). However, there is currently insufficient information on the bioavailability of nutrients in plant-based foods to cover the issue in nLCA.

Nevertheless, it is well known that plant-based foods contain compounds that may decrease the bioavailability of some nutrients. Major plant protein sources such as whole grains, legumes, nuts, and seeds are rich in phytate that binds to iron, zinc, and calcium in the small intestinal lumen and thus inhibits their absorption (Hurrell 2003). Furthermore, tannins and protease inhibitors in plant foods impair protein digestion and thus interfere with their bioavailability (Joye 2019), leading to the generally held view that plant-sourced proteins are less digestible and bioavailable than animal-sourced proteins. The amino acid profile of plant-sourced proteins is also often suboptimal, as the concentration of one or more of essential amino acids is insufficient for human needs (Vaz Patto et al. 2015).

Bioavailability issues may become important especially for vulnerable groups, including children and pregnant and lactating women with requirements for supporting active growth. The ability to digest proteins is impaired with age (Gilani et al. 2012), exposing the elderly to the risk of an inadequate nutrition status. Progress in this issue is especially important for the future nLCA development and sustainability considerations.

Another factor potentially limiting the utility of our approach is the ongoing change in dietary patterns. The plate model was the starting point for our approach, but the transition to more snack-type eating may challenge the foundations of eating as a whole—and specifically, the plate model. In this case, the product grouping thinking needs to be revised, as well as the basis for the product-group-specific nutrient indices presented in this study. Moreover, the dietary change required by the environmental perspective itself, i.e. the shift to more plant-based foods, may challenge current nutritional education tools like the plate model. The typical model plate consists of a quarter of proteins, a quarter of carbohydrates, and half of vegetables as a source of micronutrients and secondary metabolites (VRN 2014). However, plant-based protein sources such as legumes are relatively high in both protein and carbohydrates. In addition, cereals are typically considered a source of carbohydrates, but they also are an important source of protein, even in the current diet (Kaartinen et al. 2020), not to mention the targeted plant-based diets. New kinds of novel foods may also be introduced to the market. This issue could be addressed by a new type of plate model, and the product-group-specific nutrient indices could therefore be adapted to a new diet and a new plate model. The product-group-specific approach is also applicable only for products that fit the grouping, but not foods that include several groups such as ready-made meals. These products can be assessed by the across-the-board nutrient indices (Saarinen et al. 2017; McLaren et al. 2021).

Furthermore, the nutrient index represents the average nutrient content in relation to recommended intake. It may therefore result in similar index scores with different distribution of nutrients, i.e. an excess intake of one nutrient can compensate for the low concentration of another, when no capping is done (Drewnowski 2009). This is a natural feature of these indices and implies the complexity of the nutrient quality of foods. The product-group-specific approach may somewhat limit this effect compared to across-the-board indices, because the nutrients in the index are specific to the product group. In addition, the complexity of the issue is sometimes even increased by social actions targeting the improvement of public health. For example, table salt is fortified with iodine in Finland. The use of salt in food products and home cooking therefore improves the iodine status of the food but also contributes to sodium content, which can be considered an undesirable outcome. For example, this is demonstrated in the case of chickpea and pulled oats balls, which scored relatively highly in both the scarce nutrient index and the LIM index compared to other products. This stresses the need for careful consideration in terms of nutrient fortification, which has recently gained more attention, because of the quest to reduce animal-based products that are an important, and in some cases only, source of some essential nutrients.

When comparing the environmental impacts of different products, one critical issue is the representativeness and consistency of the LCAs. In this study, we have used inventory data from different sources, which is why there may be methodological differences in the background data. Also, the data derived from databases might not be representative for products commonly consumed in Finland.

Finally, one can argue that the sustainability transition should be made at diet level, and product-level assessments are therefore inadequate, although they link nutrition and environmental aspects. However, in our understanding, the rationale of product-specific assessment and information lies in the fact that consumer choices are mainly made at product level. The whole issue of food sustainability is not be solved by consumers, but consumers should be included in the transition process. It is matter of how to do this. The product level information is also easier to utilise than diet-level assessments by other actors in the value chains, such as agricultural producers and food processing industry.

The product-group-specific approach presented in this paper is tightly tied to a more comprehensive diet level by selecting nutrients for nutrient indices. However, this does not mean this approach, or any other approach, can prove that some products should or should not be consumed, but rather addresses relative differences that hopefully could influence the frequency of the consumption of products. In the background, diet-level considerations are also very important for forming an overall picture and monitoring the development of the situation.

5 Conclusions

Product-group-specific nFUs can be used to assess the environmental impacts of substituting one product in a specific product group with another, without compromising nutritional quality. The index used as the nFU should be formatted based on the study goal and scope, as well as the population under study, because age-group-based recommendations have a clear impact on the index score, and the criteria for the included nutrients may be varied based on the population in question. No single index can therefore be used for all purposes, and the formation of the nFU index should always be explained with clear criteria and justification.

However, the baseline nutrient index introduced in the study, as well as the procedure for selecting nutrients for it, seems valid for producing relevant sustainability information regarding protein sources and supporting the aspiration for a sustainable dietary shift. Products based on plant proteins or especially fish seem to be particularly sensitive to reacting to differences in nutrient indices, which makes the integration of nutritional quality into the environmental Life Cycle Assessment of foods particularly important in the context of a sustainability-oriented diet change. Vulnerable groups must be considered when interpreting the results.

Because the nFU expresses the environmental impact only in relation to a group of beneficial nutrients, the nutrients to limit should also be assessed separately when comparing products with the nLCA. More research is required into the inclusion of nutrient bioavailability in the indices, how to consider equality among a varied population, and how to consistently apply the nFUs in a wide range of nLCA studies.

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Data availability All data generated during this study are included in this published article and other data is available in the sources given.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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