The International Journal of Life Cycle Assessment (2025) 30:682–693
https://doi.org/10.1007/s11367-024-02422-7

LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Adapting the product group-specific nutritional functional units to the Spanish context

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Received: 29 October 2024 / Accepted: 17 December 2024 / Published online: 9 January 2025

Abstract

Purpose Nutritional aspects have recently been integrated into the life cycle assessment (LCA) of foods through the use of nutrient indices as functional units (nFU). In this study, we develop the nFU indices for each product group presented in the Spanish plate model, by adapting the approach introduced in our previous studies into a Spanish context.

Methods The product grouping followed the Spanish plate model covering protein-rich foods, sources of carbohydrates, vegetables and fruits, and fats. For each group, separate nFUs were created by identifying the most important nutrients for each product group, based on the nutrients obtained from them in the current Spanish food consumption. Finally, the new nFUs were showcased by conducting cradle-to-plate nLCA for the selection of typical Spanish foods.

Results and discussion Adapting the method to formulate the nFUs to different target population led to different selection of nutrients being included in the indices for each product group, highlighting the need to tailor the methodology depending on the population under study. The nLCA results demonstrated the importance of integrating nutritional aspects into comparative LCAs of foods in all the studied product groups, also including the new product group of fats, which was the first time used in nLCA in this study.

Conclusions The results demonstrated that the product-group-specific approach is a systematic and reproducible method to formulate nFU indices and that it can be consistently adapted also to other target populations with relevant data available. For more extensive coverage of health aspects in LCA, the inclusion of non-nutrient compounds should be promoted.

Keywords NLCA · Nutrient index · Functional unit · Sustainable nutrition · Dietary shift · Meals

1 Introduction

Life cycle assessment (LCA) studies of food products are evolving to incorporate nutritional considerations to capture the possible trade-offs between nutrition and environmental sustainability and to improve the comparability of food's environmental impacts. Recent advancements, synthesized by McLaren et al. (2021), have led to the development of nutritional LCA (nLCA), which enables a comparison of food products based on both environmental and nutritional criteria. Especially the adoption of nutrient indices as the functional unit (FU) has been suggested, to capture the nutritional complexity of products more thoroughly than traditional mass-based or single nutrient units.

The nutritional FUs (nFU) can be general across-the-board indices applicable to all food products, such as nutrient rich food (NRF) indices, or product-group-specific, which are suitable for distinguishing product choices within the product group (McLaren et al. 2021). Thus, understanding and developing guidance for using and creating product group-specific metrics for relevant food groups has been identified as one of the research needs to progress towards a harmonized nLCA methodology (McLaren et al. 2021).

Communicated by Matthias Finkbeiner.

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Previous studies have presented product-group-specific nutrient indices to be used as a nFU in nLCA. Most of the developments have been focused on product group of protein-rich foods (e.g. Green et al. 2021; Kyttä et al. 2023a; McAuliffe et al. 2018; Saarinen et al. 2017), but recently indices for product groups of sources of carbohydrates and vegetables, fruits, and berries have also been introduced (Kyttä et al. 2023b).

The goal of using product-group specific nFUs is to enable comparison between products which are alternatives to each other in eating practices. This is achieved by including the nutrients important for the product group in the nFU. The approach to formulate product-group- and population-specific nFUs presented by Saarinen et al. (2017) and further defined by Kyttä et al. (2023a; 2023b) is based on product grouping which follows the grouping of the plate model presented in Finnish nutrition recommendations (VRN 2014) including half a plate of vegetables, a quarter of a plate of a carbohydrate source, and a quarter of a plate of a protein source, complemented by a drink and a bread with a soft vegetable fat spread. Similar models to guide consumers on compiling healthy and balanced meals are presented in dietary guidelines in multiple regions across the world (FAO 2023). The grouping based on such models aims to represent the components of a meal, within which consumers choose individual food products to promote a balanced, healthy diet. To capture the nutritional function of each product group, the nutrients in the nFU indices are chosen based on the current food consumption of the population under study by tracking which product groups are the most important sources of each nutrient (Kyttä et al. 2023a; 2023b). To adapt a similar approach to countries with different gastronomic cultures, the methodology needs to be reviewed by revising the product grouping based on the local food consumption data, selecting the nutrients for the nFU indices based on the food consumption of the population under study and calculating the nutrient indices using the national nutrition recommendations.

Here, we adapt the product-group specific approach by Kyttä et al. (2023a; 2023b) to develop product-group-specific nutrients rich index (NR) family to be used as nFUs in the Spanish context (NR-SP), covering the product groups presented in the Spanish plate model: protein-rich foods, sources of carbohydrates, vegetables and fruits, and fats. In this study, the approach is applied to fats for the first time. First, the protocol to formulate the nFU indices for each product group in the Spanish context is presented, and the application of the developed nFUs is then showcased through an assessment of typical Spanish foods in each product group.

2 Materials and methods

2.1 Selection of nutrients for indices: food grouping and nutrient intake

The product-group specific approach to formulate nFUs used in nLCA defined by Kyttä et al. (2023a; 2023b) and partially validated by Kårlund et al. (2024) was adapted to the Spanish dietary context. To systematically reproduce the product-group-specific nFUs to other target population, the following adaptations are needed:

i) Product grouping representing the gastronomic culture and food consumption habits of the population under study based on grouping presented in the national nutrition recommendations.

ii) Selecting the most and second most obtained nutrients from the product groups to the nFU indices based on the food consumption and nutrient intake data of the population under study.

iii) Calculating the nutrient indices using the dietary reference intakes given in the national nutrition recommendations.

The product grouping and selection of nutrients for the Spanish food indices was based on the nutrient intake from the different food sources reported by the ANIBES study for macronutrients (Ruíz et al. 2016) and micronutrients such as niacin (vitamin B3), riboflavin (vitamin B2), thiamine (vitamin B1) and pyridoxine (vitamin B6) (Mielgo-Ayuso et al. 2018); selenium (Se), vitamin A, vitamin E and vitamin C (Olza et al. 2017a); calcium (Ca), phosphorous (P), magnesium (Mg) and vitamin D (Olza et al. 2017b); folate and vitamin B12 (Partearroyo et al. 2017); and iron (Fe) (Samaniego-Vaesken et al. 2017). Potassium (K), iodine (I) and vitamin K intakes from the different food sources were not reported in the abovementioned study; thus, they were not included in this research. Food sources were classified into product groups representing the different meal components of a "healthy plate," which shows the proportion of the different food groups that need to be ingested throughout the day to achieve a healthy diet (Harvard University 2011). It states that half of the plate (50%) should be composed of vegetables and fruits, one quarter (25%) of protein sources and one quarter (25%) of carbohydrate sources. Likewise, the use of olive oil as the main fat source is recommended in the Spanish version of the "healthy plate" (AESAN, Agencia Española de Sguridad Alimentaria y Nutrición, 2022a). According to that grouping, the classification of food sources from the ANIBES study into product groups defined in the "healthy plate" was done as listed in Table 1.

Milk and dairy products were excluded from the study because milk is commonly consumed as a drink rather than

Table 1 Classification of food sources reported in ANIBES study into food product groups

Food product group	Food source
Vegetables	• Vegetables • Fruits
Proteins	• Fish and shellfish • Meats • Sausages and other meat products • Viscera and offal/spoils • Eggs • Legumes
Carbohydrates	• Grains and flours • Bread • Breakfast cereals and cereal bars • Pasta • Bakery and pastry
Oils and fats	• Olive oils • Other oils • Butter, margarine and shortening

as a part of a protein portion. Additionally, dairy products (e.g. cheese, yoghurt) are commonly consumed as delicacies, toppings, seasonings, snacks or desserts. Other specific food sources (e.g. sweets, chocolate, jams) and drinks (e.g. water, coffee, tea, soft drinks) were not considered in this study.

The criterion for incorporating specific nutrients into the index required that the group under study was the most or the second most abundant source of that specific nutrient. Based on that, the nutrient selection for the indices of the different food groups (for vegetables and fruits NR-SPveg, for protein-rich foods NR-SPprot, for sources of carbohydrates NR-SPcarb, and for fats NR-SPfats) for the Spanish population was formatted. The nutrients included in each index are shown in Table 2 in the "Results" section.

2.2 Demonstrative LCA of food products

Selection of foods representative of Spanish household consumption were assessed as a demonstrative case study using attributional LCA. The choice of the foods was based on the "Report of food consumption in Spain" (MAPA, Ministerio de Agricultura, Pesca y Alimentación, 2023), in which a ranking of the most cooked recipes in Spanish households is presented, including vegetable-based recipes (green beans, green salad and tomato salad), protein-based recipes (omelette, hake, lentils, pork loin, potato omelette) and carbohydrate-based recipes (potato omelette, pasta soup, macaroni). In addition, for the carbohydrate-based recipes, a paella recipe was included in the study. Most of the recipes were obtained from a popular Spanish cookbook (Ortega 1972). For foods that did not appear in the cookbook, a cooking blog was consulted (Bon Viveur 2024). For the fats group, extra virgin olive oil, sunflower oil, rapeseed oil, palm oil and butter without cooking phase were considered. The recipes of the assessed foods are presented in the supplementary materials (S.1). All the units were converted to grams, and the quantities were adjusted for a final 100-g ready-to-eat meal portion. Likewise, the food waste generated during the cooking processes (e.g. shells, peels, bones) was accounted based on Finnish food measures (Sääksjärvi and Reinivuo 2004) and USDA (2018).

The nutrient composition of the recipes was calculated per 100 g of cooked portion using the National Food Composition Database in Finland (THL (National Institute for Health and Welfare), 2024). Nutrient retention factors derived from the different cooking methods were considered based on Vásquez-Caicedo et al. (2008). To determine the nutrient composition of fats, the Spanish food composition database (BEDCA 2007) was used. The nutritional assessment of each recipe is presented in the supplementary materials (S2).

2.2.1 Calculation of the nutrient indices: nFU

As in the previous studies by Kyttä et al. (2023a; 2023b) and Saarinen et al. (2017), the formula suggested by Fulgoni et al. (2009) was used for calculating the nutrient indices of specific food (nFU):

Table 2 Selection of nutrients for food group indices. The nutrients in bold are the same as in the Finnish NR-FI indices

Nutrient index	Nº of nutrients	Nutrients
NR-SPveg	7	Carbohydrates, **fibre**, **vitamin A**, pyridoxine (vitamin B6), folate (vitamin B 9), **vitamin C**, calcium (Ca)
NR-SPprot	18	**Proteins**, monounsaturated fatty acids (MUFA), polyunsaturated fatty acids (PUFA), vitamin A, vitamin D, vitamin E, **thiamine (vitamin B1)**, **riboflavin (vitamin B2), niacin (vitamin B3), pyridoxine (vitamin B6)**, folate (vitamin B9), vitamin C, **vitamin B12**, phosphorous (P), magnesium (Mg), **iron (Fe)**, **selenium (Se)**, **zinc (Zn)**
NR-SPcarb	14	**Carbohydrates, fibre,** proteins, vitamin D, thiamine (vitamin B1), riboflavin (vitamin B2), niacin (vitamin B3), vitamin B12, **phosphorous (P)**, calcium (Ca), **magnesium (Mg)**, **iron (Fe)**, selenium (Se), zinc (Zn)
NR-SPfats	3	MUFA, PUFA, vitamin E

$$Index = \sum \frac{NUTRIENTi}{DRIi} x100/numberofnutrientsintheindex$$

where *nutrient i* is the content of a selected nutrient in 100 g of a product and *DRIi* is the dietary reference intake for the nutrient given in nutrition recommendations. Reference intakes for the Spanish population were taken from AESAN Agencia Española de Seguridad Alimentaria y Nutrición (2019). In the case of proteins and fats, monounsaturated fatty acid (MUFA) and polyunsaturated fatty acids (PUFA), data was taken based on the nutritional objectives for the Spanish population (Moreiras et al. 2018). Reference intakes are shown in supplementary materials (S3).

The nutrient index scores were calculated for different age groups and sexes which have their own reference intakes (AESAN, Agencia Española de Seguridad Alimentaria y Nutrición, 2019). Since the daily intake recommendations for energy and fibre have different age groupings compared to the other nutrients, these values were averaged to align with the same age ranges. The population groups under study were as follows: children aged 1–3, 4–5 and 6–9 and male and female aged 10–13, 14–19, 20–29, 30–39, 40–49, 50–59, 60–69 and ≥ 70.

2.2.2 Environmental impact assessment

The environmental impact was assessed for 100 g of ready-to-eat food. The system boundaries included the whole life cycle from the production of the ingredients to the final meal ("cradle to plate" scope). The transportation from the supermarket to households was not accounted for due to a lack of data. Data on the ingredients was obtained from Agribalyse 3.1 (Asselin-Balençon et al. 2022). For the cooking methods, World Food LCA Database 3.5 was used (Nemecek et al. 2019), considering the cooking time and quantity of food. In cooking, electricity was assumed as an energy source and share of energy generation sources were collected from the Spanish electricity distribution company for the year 2023 (REE. Red Eléctrica Española 2024). Two methods were applied for the quantification of the environmental impacts: (i) IPCC 2021 GWP100 to enable comparison to earlier studies where only climate impacts have been assessed (Kyttä et al. 2023a, 2023b) and (ii) ReCiPe 2016 Endpoint (E) to consider also the other environmental impacts and provide a more holistic assessment, as the final single score results consider human health, together with ecosystem quality and resource scarcity as endpoint areas of protection (Huijbregts et al. 2017). The modelling was done using SimaPro 9.5 software (PRé Sustainability 2023). Finally, to assess the environmental impact per nFU, the environmental impact (per 100 g) of the foods under study was divided by their nutrient index score (per 100 g).

3 Results

The results of the environmental impact assessment of the different foods included in the study are shown in Figs. 1, 2, 3, and 4 for the two methods selected (IPCC 2021 GWP100 and Recipe 2016 Endpoint). All the data of the results is also provided in the supplementary material (S4). Limited contribution of the cooking phase is observed in most of the recipes for GWP100 category, but it becomes very relevant when the Recipe 2016 Endpoint method is assessed. An important share of the Spanish electricity mix comes from renewable or nuclear sources, which mitigates the impact on climate change from electricity consumption for cooking. However, ReCiPe method integrates 22 different impact categories in a single score, involving weighting and normalization for three main damage areas (Human health, Ecosystems and Resources). In this case, the impact of the manufacturing and use of cookware (e.g. pan, pot, stoves) becomes more relevant, especially through their contribution to "Human health" damage category.

3.1 Spanish product group-specific nutrient indices

The protocol of creating product-group-specific nutrient indices for the Spanish population resulted in the NR-SP index family, which covers product groups of vegetables and fruits, protein-rich foods, sources of carbohydrates and fats. The nutrients considered in each index are presented in Table 2.

3.2 Demonstrative LCAs

3.2.1 Vegetables

In the nutrient index score for the vegetables group (NR-SPveg), the children obtained the highest values in all the foods and males aged 30–39 the lowest. Among the studied vegetable-based recipes, green beans obtained slightly higher nutrient index scores (Fig. 1a). Likewise, green beans had the highest environmental impacts (0.08 kg CO_2eq.; 13.33 mPt), mainly due to the associated cooking processes (boiling green beans and frying the garlic included in the recipe) (Fig. 1b). Besides, when assessing the environmental impact per nutrient index score, green beans showed the highest values (mean = 0.01 CO_2eq./NR-SPveg and 1.57 mPt/NR-SPveg) (Fig. 1c).

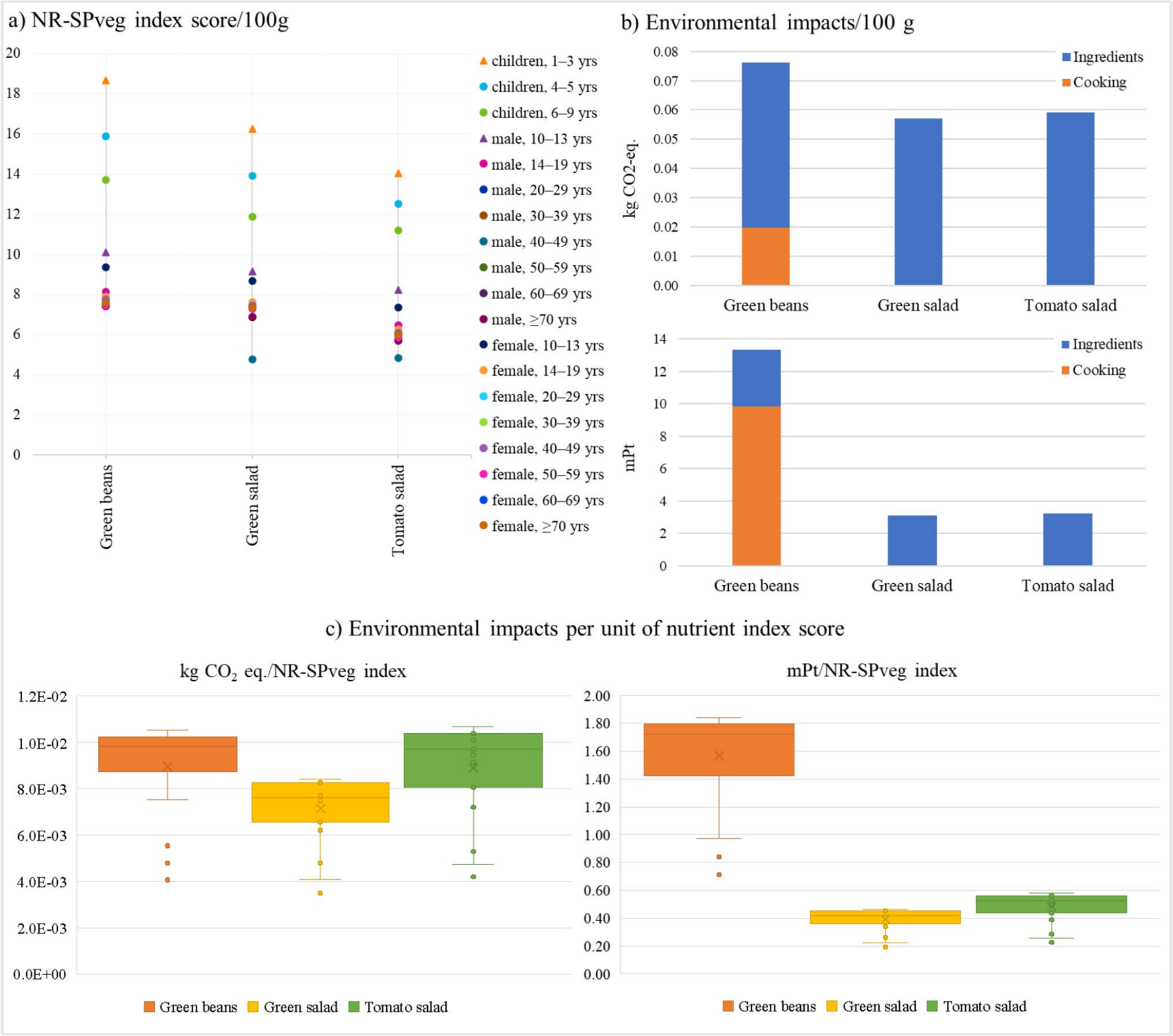

Fig. 1 **a** NR-SPveg nutrient index scores per 100 g for each population group. **b** Environmental impacts as climate impacts (IPCC 2021 GWP100) and a ReCiPe 2016 Endpoint single score per 100 g. **c** Environmental impacts per unit of NR-SPveg index. In the box plot figures, the lowest results represent the results for children due to lower nutrient intake recommendations, while the cross represents the mean and the line the median of the population groups. The data used to create the figures are given in the supplementary material (S4)

3.2.2 Proteins

In the nutrient index score for the protein group (NR-SPprot), the children obtained the highest values, and the males (30–39 years) the lowest. Regarding the recipes, omelette obtained the highest nutrient index scores (Fig. 2a). According to the environmental impact, pork loin (1.25 kg CO_2 eq.) and hake (54.54 mPt) were the meals with the highest impacts and lentils (0.05 kg $CO_{2;}$ 17.34 mPt) the lowest (Fig. 2b). When assessing the climate impact of the meals per unit of nutrient index score, pork loin showed the highest values (mean = 0.06 kg CO_2 eq./NR-SPprot). However, when assessing mPt per NR-SPprot index, the results showed that lentils had the highest values (mean = 6.03 mPt/NR-SPprot) (Fig. 2c). This can be explained because the cooking time of the lentils meal (which includes sautéing minor ingredients such as vegetables and boiling) is relatively longer than the other studied recipes. In addition, when using the IPCC 2021 GWP 100 method, the impact mainly comes from emissions related to energy consumption during cooking. However, with the ReCiPe 2016 Endpoint (E) method, in addition to this, a broader set of impacts are considered,

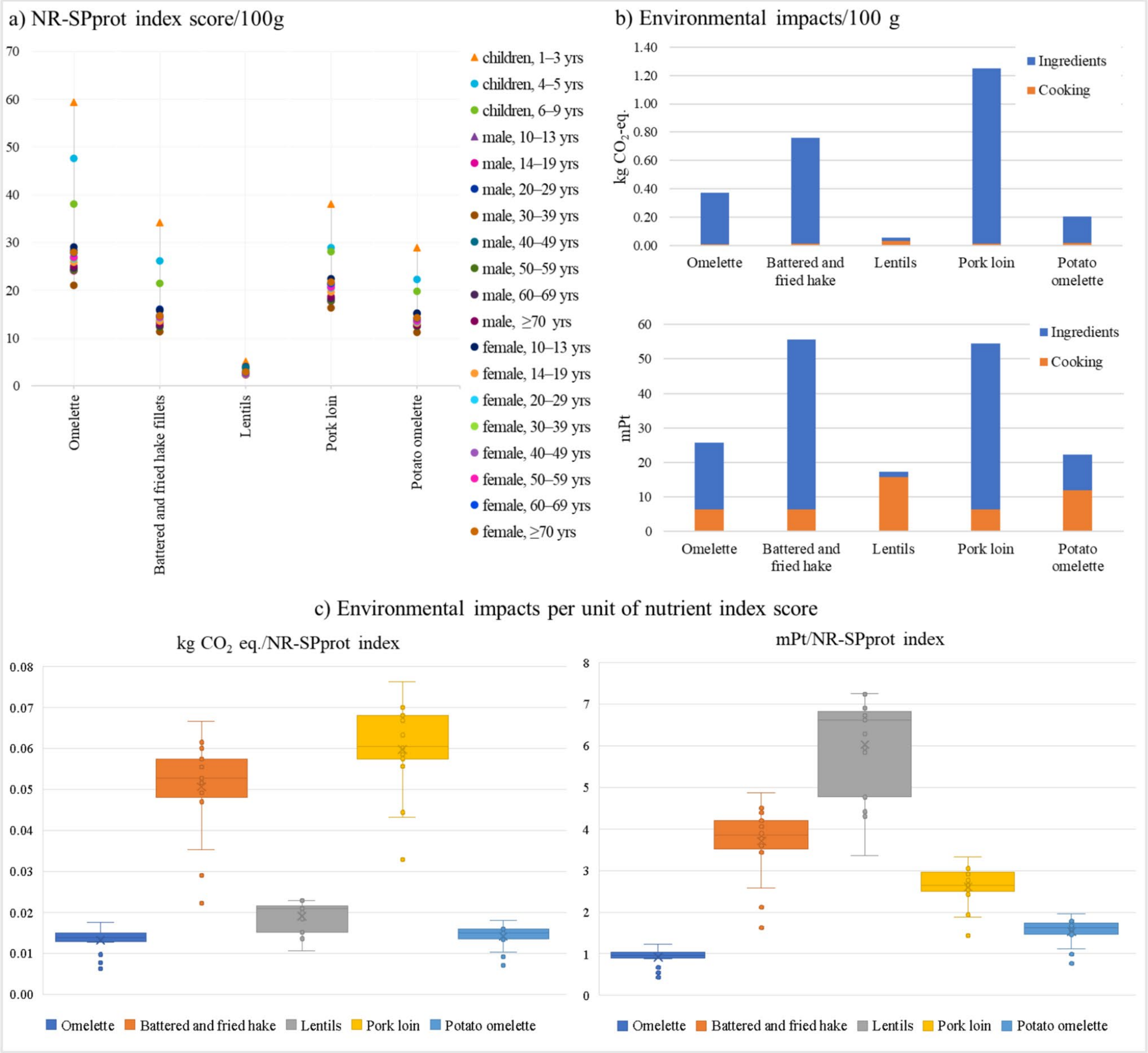

Fig. 2 **a** NR-SPprot nutrient index scores per 100 g for each population group. **b** Environmental impacts as climate impacts (IPCC 2021 GWP100) and a ReCiPe 2016 Endpoint single score per 100 g. **c** Environmental impacts and per unit of NR-SPprot index. In the box plot figures, the lowest results represent the results for children due to lower nutrient intake recommendations, while the cross represents the mean and the line the median of the population groups. The data used to create the figures are given in the supplementary material (S4)

emphasizing the importance of manufacturing and using cookware (Fig. 2).

3.2.3 Carbohydrates

In the nutrient index score for carbohydrates group (NR-SPcarb) the children obtained the highest values and males 30–39 the lowest. Regarding the meals, potato omelette obtained the highest nutrient index scores and pasta soup the lowest (Fig. 3a). Concerning the environmental impact, paella (0.44 kg CO_2 eq.; 44.33 mPt) was the meal with the highest impacts (Fig. 3b). However, when assessing the environmental impact per nutrient index score, pasta soup showed the highest values (mean = 0.26 kg CO_2eq./NR-SPcarb; mean = 21.68 mPt/NR-SPcarb) and potato omelette the lowest (mean = 0.03 kg CO_2eq./NR-SPcarb; mean = 1.92 mPt/ NR-SPcarb) (Fig. 3c).

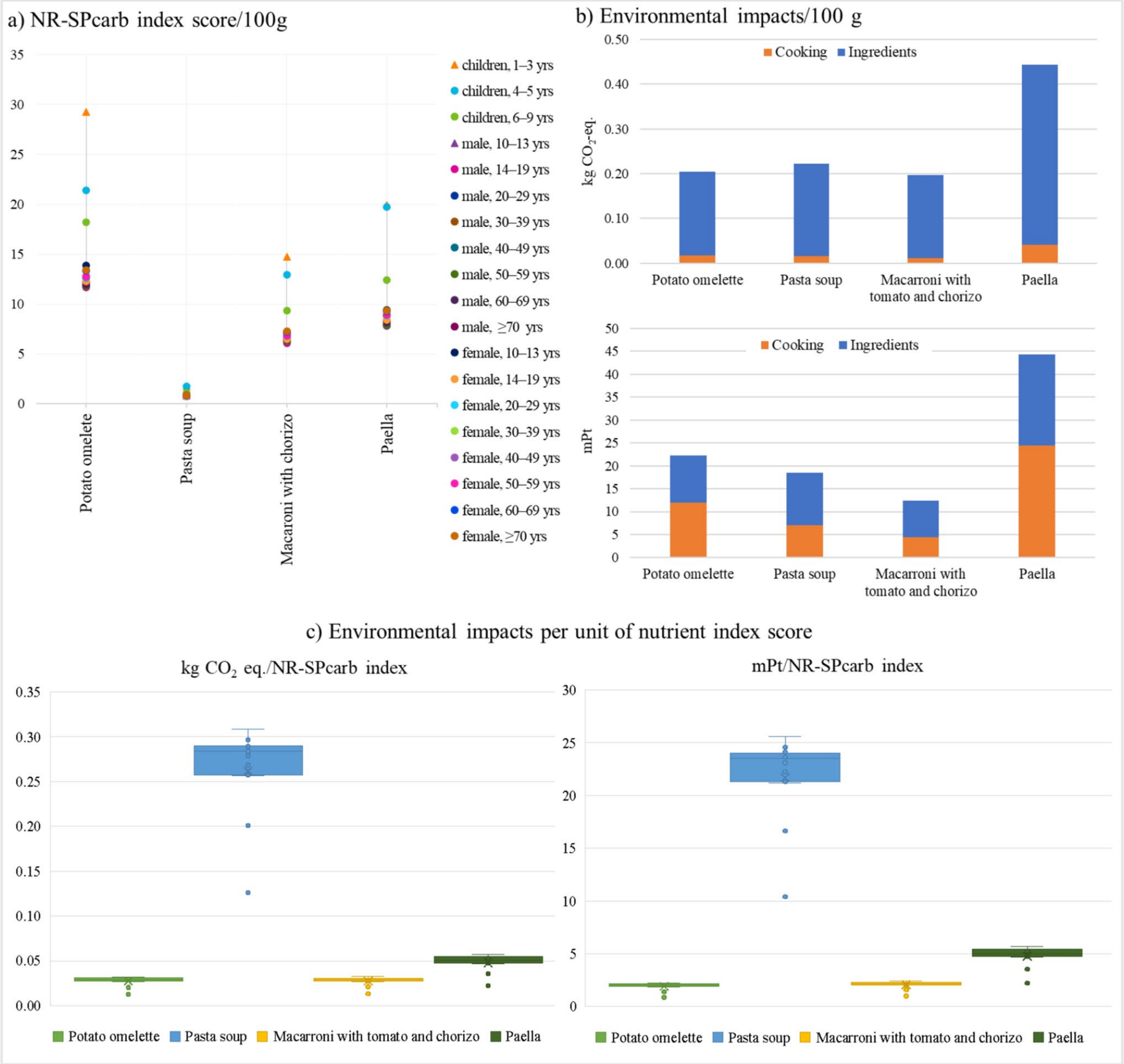

Fig. 3 **a** NR-SPcarb nutrient index scores per 100 g for each population group. **b** Environmental impacts as climate impacts (IPCC 2021 GWP100) and a ReCiPe 2016 Endpoint single score per 100 g. **c** Environmental impacts per unit of NR-SPcarb index. In the box plot figures, the lowest results represent the results for children due to lower nutrient intake recommendations, while the cross represents the mean and the line the median of the population groups. The data used to create the figures are given in the supplementary material (S4)

3.2.4 Fats

In the nutrient index score for the fats group (NR-SPfats), the children obtained the highest values and the males (14–19 years) the lowest. Among the studied fats, sunflower oil obtained the highest nutrient index scores and butter the lowest. The environmental impacts of butter (0.77 kg CO_2 eq.) and palm oil (30.10 mPt) were the highest and extra virgin olive oil the lowest (0.10 kg CO_2 eq.; 5.86 mPt). However, when assessing the environmental impact per NR-SPfats, butter showed the highest values in both impact categories (mean = 0.02 kg CO_2 eq./NR-SPfats; mean = 0.72 mPt/ NR-SPfats). When assessing with the IPCC 2021 GWP 100 method, extra virgin olive oil, sunflower oil, and rapeseed oil showed the lowest values (mean = 0.001 kg CO_2 eq./NR-SPfats), and with ReCipe single score method, extra virgin olive oil and sunflower oil (mean = 0.04 mPt/NR-SPfats) remained the fats with the lowest impacts (Fig. 4).

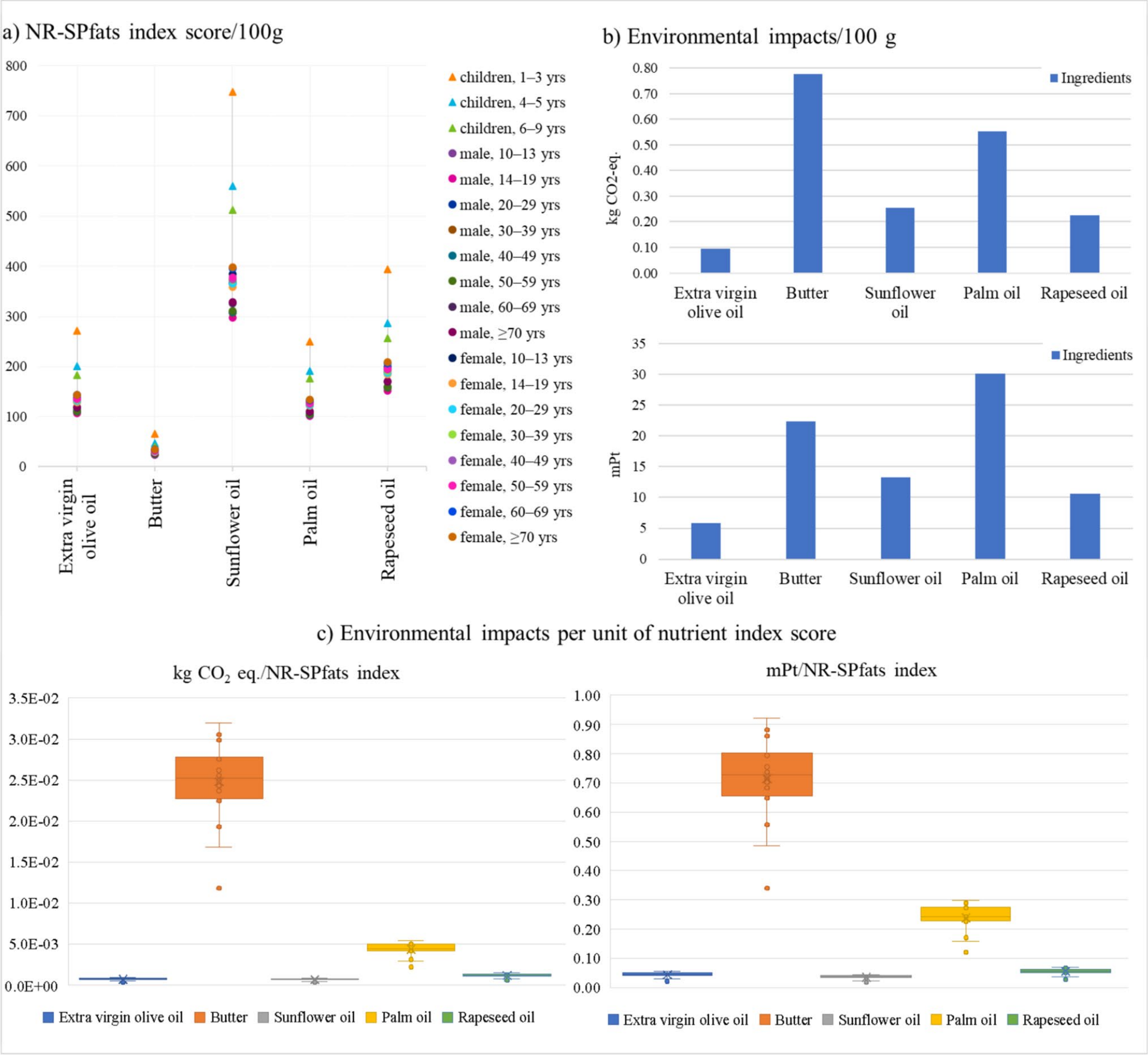

Fig. 4 **a** The NR-SPfats nutrient index scores per 100 g for each population group. **b** Environmental impacts as climate impacts (IPCC 2021 GWP100) and a ReCiPe 2016 Endpoint single score per 100 g. **c** Environmental impacts and per unit of NR-SPfats index. In the box plot figures, the lowest results represent the results for children due to lower nutrient intake recommendations, while the cross represents the mean and the line the median of the population groups. The data used to create the figures are given in the supplementary material (S4)

4 Discussion

In this study, we have adapted the methodology to formulate nFUs presented by Kyttä et al. (2023a; 2023b) into a Spanish context by creating product-group-specific nutrient indices for product groups of vegetables and fruits, protein-rich foods, and sources of carbohydrates. As an addition to the previously covered product groups, here, we have also considered the product group of fats and oils.

The results demonstrated that the product-group-specific approach can—and should—be adapted for different populations because basing the formation of the indices on another population led to different selection of nutrients being included in the indices. Here, the product grouping was similar to the previous study by Kyttä et al. (2023a, b), but in other contexts, the grouping might also differ due to different eating habits. In addition, the recommended intake of each nutrient varies between nations, and therefore, also the recommendations used in the index calculation should always be based on the recommendations of the target population (McLaren et al. 2021). The recommended intakes are also given separately for different population groups (age groups, sexes), which, as demonstrated here, leads to different results for each population group. Due to the highest nutrient intake recommendations, the index scores for males are typically the lowest, and the ones for children the highest, resulting in the highest environmental impacts for men and the lowest for children. However, when using index scores as the FU, the amount from which the nutrient index score and the environmental impacts are assessed does not change the results, as the relation between environmental impacts and nutrition will remain the same. The matter is further discussed in the previous publications (e.g. Kyttä et al. 2023a; Saarinen et al. 2017).

4.1 Adaptation of the approach to the Spanish context

Some differences were shown in the composition of the different Spanish nutrient indices compared to Finnish ones (Kyttä et al. 2023a, 2023b). In the case of *protein-rich foods*, the number of nutrients included in the NR-SPprot (18 nutrients) was higher than in the NR-FINprot (10 nutrients). In the Spanish context, meat, eggs, fish and shellfish, eggs and legumes were identified as protein sources. This is much wider selection of products than in the Finnish context, where nutrients for the NR-FINprot index were selected based on the consumption of meat, eggs and/or dairy products (Kyttä et al. 2023a). Indeed, in the Finnish case, dairy products were originally included in the protein component of a plate model although they are consumed more as a drink in meals. Afterwards, milk has also been studied as a separate product group, and the nFU for milk consumed as a drink has been developed in a Finnish context (Kovanen et al. 2024). In general, milk and dairy products are difficult to be categorized as such a varied product group. This should be addressed more in the future research.

Regarding the product group of *vegetables*, some specific nutrients were also selected in each of the countries (Table 2). For example, in the Spanish case, carbohydrates are included in the NR-SPveg index. It should be noted that in the reference study used to identify nutrient intake sources, potatoes are included in the “vegetables” group, while, in a dietary approach, potatoes are considered as a source of carbohydrates due to their high starch content rather than as a vegetable (AESAN, Agencia Española de Seguridad Alimentaria y Nutrición, 2022b). It underscores the importance of harmonizing food classification.

In the case of sources of *carbohydrates*, in the Finnish context, two specific nutrients are included in the NR-FINcarb index (folate and potassium (K)), and in the Spanish adaptation, seven specific ones were added (proteins, vitamin D, thiamine (B1), riboflavin (B2), niacin (B3), selenium (Se), and zinc (Zn)) in addition to the nutrients included in both indices. These results highlight the importance of considering the sources of food intake of the population when assessing sustainable and healthy diets, which can vary widely across food cultures (Sproesser et al. 2022).

In addition to the product groups discussed above, to our knowledge, the first nFU for fats was introduced in this paper. The number of nutrients included in the index was relatively low, covering only three nutrients (MUFA, PUFA, and vitamin E). The Finnish NR-FI indices (Kyttä et al. 2023b) do not currently cover the product group of fats, but the nutrients included in NR-SPfats are absent from the NR-FI indices, suggesting that the NR-FIfats index could be similar to the Spanish one.

4.2 Performance of the new indices

The results of the demonstrative LCAs showed that using the new nFUs instead of mass-based FUs changes the relative environmental impacts between assessed products, leading to relatively lower impacts for foods with high nutritional value. This approach suggests that new metrics should be considered when measuring the sustainability features of foods. However, the nLCAs done in this study were made to present, test, and evaluate the new nFUs, and generalizations based on the results of individual products in this study should not be done, since the results are highly dependent on the choice of recipes and data sources for environmental impacts and nutrition content.

In the product group of *vegetables*, green beans had the highest nutrient index scores but also notably higher environmental impacts than green salad and tomato salad, resulting in the highest environmental impacts per unit of NR-SPveg index. The results of the vegetables also demonstrated how the inclusion of the cooking phase can have a considerable influence on the results. Also, in the product group of *protein-rich* foods, the cooking phase had a notable contribution to the environmental impacts, especially in the case of lentils, which had otherwise low environmental impacts. The best-performing products in the product group of protein-rich foods were omelette and potato omelette, which had relatively high nutrient index scores and mediocre environmental impacts leading to the lowest impacts per unit of the NR-SPprot index. Potato omelette was also assessed as a source of *carbohydrates* using the NR-SPcarb index. The results for potato omelette were similar in both product groups, as it is dense in the nutrients proposed for both indices. Likewise, it had the lowest environmental impacts per unit of index also compared to other assessed products in the group of carbohydrate sources. The worst-performing product in the group was pasta soup affected by a very low nutrient index score. Other assessed foods, macaroni with tomato and chorizo and paella, also resulted in relatively low environmental impacts per unit of NR-SPcarb index compared to pasta soup.

In the product group of fats, the performance of the assessed products demonstrated that both the nutritional content and the environmental impacts of different fat sources vary notably, showing that integrating nutritional aspects also into the LCA of fats is justifiable. In this product group, butter and palm oil performed the worst affected by both high environmental impacts and low nutrient index scores. All the other assessed oils (extra virgin olive oil, sunflower oil, rapeseed oil) had considerably lower environmental impacts per unit of NR-SPfats index, and the differences between these oils were low.

4.3 Strengths, limitations, and future considerations of the methodology

The approach to formulating the nutrient indices presented by Kyttä et al. (2023a; 2023b) and adapted here to the Spanish context is a systematic approach to formulate the indices and therefore can be consistently adapted also for other target populations by following the same logic. As a reproducible and coherent procedure, the approach can also be considered an advancement to harmonize the nLCA methodology. Due to cultural differences, the method needs to be tailored based on the context and target population (McLaren et al. 2021), but the approach presented in our earlier studies (Kyttä et al. 2023a; 2023b), and adapted here, provides a starting point for a consistent methodology.

The new nFU indices developed in this study can be used to assess the environmental impacts of choosing different foods within a product group, considering the nutritional consequences to the Spanish population. Assessments done by applying these nFUs can bring new information to discussion about sustainable food choices. However, as noted by Saarinen et al. (2017) and instructed by McLaren et al. (2021), to ease the interpretation and increase the usability of the results, also the reference flows per nFU should be reported or mass/volume-based FUs should be used in addition to nFU. In addition, information gained by this product group-specific approach should be added by considering nutrients harmful to health in typical portions as has been previously stated (Saarinen et al. 2017; McLaren et al. 2021). This can be done by a specific nutrient index for those nutrients, so-called LIM index (Saarinen et al. 2017), or by assessing health impacts as an impact category (Stylianou et al. 2021), although more research should be done to develop these methodologies (McLaren et al. 2021).

The limitation of the product group-specific nFUs is the fact that not all foods fit the product grouping. For example, in this study, we have included potato omelette in the product groups of protein-rich foods, as well as in sources of carbohydrates. Because the fundamental idea of product grouping is to categorize foods which are consumed similarly—and thus between which actual consumption choices are typically made—into the same group, products that belong to more than one group might appear challenging. For the assessment of mixed foods and meals, a combination of two or more indices, such as nutrients from NR-SPcarb index and NR-SPprot index, to assess foods like potato omelette could be a step forward, but the issue requires further research. Likewise, many of the recipes categorized in one specific food group also contained other minor ingredients belonging to other groups (e.g. paella, in addition to containing rice, also contained chicken, rabbit and other ingredients). For whole meals, which include components from each product group, general across-the-broad nutrient indices may be the most appropriate (Saarinen et al. 2017; McLaren et al. 2021; Kyttä et al. 2023b), but detailed research on the issue is lacking.

Because the indices are calculated as a nutrient content in relation to the recommended intake, only nutrients with DRI can be included. While the index-based nFUs are relatively easy to apply, this inevitably limits the nutrients that can be considered in the nLCA. Similarly, to include the health aspects more holistically, the possibilities to include non-nutrient compounds should be examined. For example, a key aspect that differentiates fats is their content of bioactive non-nutrient compounds. In the case of extra virgin olive oil, its minor composition of polyphenols and phenolic compounds (approximately 2% of the weight) (Mazzocchi et al. 2019) has shown to have several health benefits (Jimenez-Lopez et al. 2020), for example, decreasing the risk of diseases such as coronary heart diseases (CHD), metabolic syndrome, and type 2 diabetes. Likewise, it has been shown to be effective for weight loss and long-term weight control (Flynn et al. 2023). This also applies to the vegetables, fruits, and berries group in which many products typically contain several secondary metabolites in high quantities, particularly berries.

Finally, in the presented case study, it has been assumed that the ingredients used in the recipes come from average production at national level from French database Agribalyse 3.1 (Asselin-Balençon et al. 2022). However, the environmental impact of food production can vary depending on the agricultural/farm methods used (Boschiero et al. 2023), which could lead to different results. Also, when conducting an nLCA study for foods with multiple ingredients, the results depend on the specific ingredients, their quantities, and the cooking time and methods used. However, previous research has shown that changing the cooking method or substituting ingredients other than the main one does not significantly impact the results (Kyttä et al. 2023a). In contrast, it has been demonstrated that including the cooking phase in the assessment is more critical than altering the cooking method or secondary ingredients. This is because the cooking process influences both environmental impacts and nutrient indices through mass loss (which increases nutrient density) and nutrient content loss (which decreases nutrient density).

5 Conclusions

The study underscores the crucial importance of considering both environmental and nutritional aspects when assessing the sustainability of foods. The intersectionality of these factors necessitates a holistic approach to ensure that our food systems are not only environmentally friendly but also contribute to the overall health and well-being of the people. Recognizing the inherent influence of cultural context on food consumption habits, our findings emphasize the need for tailoring assessment methods to the specific characteristics of the population under study. By demonstrating the adaptability of product group-specific indices in a systematic and reproducible manner, this study contributes to the evolving field of nLCA.

The development and implementation of a systematic and reproducible methodology are pivotal steps in advancing the harmonization of the nLCA method. Such standardization not only enhances the reliability of results but also facilitates a more comprehensive and universally applicable approach to evaluating the sustainability of food products. Looking ahead, continued collaboration and refinement of methodologies will be essential to meet the evolving challenges in ensuring a sustainable and nutritious global food supply.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-024-02422-7.

Author contribution Paula Torán-Pereg and Venla Kyttä contributed equally to the conceptualization and execution of this study. Guillermo Pardo contributed to the formal analysis and writing, and Merja Saarinen to the writing and supervision of this work.

Funding Open access funding provided by Natural Resources Institute Finland. The work done by Venla Kyttä and Merja Saarinen in this study was funded by the Ministry of Agriculture and Forestry (the Development Fund for Agriculture and Forestry) and the stakeholder companies Atria Oyj, Helsingin Mylly Oy, Kesko Oyj, Oy, Karl Fazer Ab, Oy Soya Ab, Vaasan Oy and Valio Oy.

The work done by Paula Torán-Pereg in this study was funded by the Basque Government (Departamento de Desarrollo Económico e Infraestructuras de la Viceconsejería de Agricultura, Pesca e Industria Alimentaria del Gobierno Vasco).

Financial support for BC3 research was provided by the Spanish Government through María de Maeztu excellence accreditation 2023–2026 (Ref. CEX2021-001201-M, funded by MCIN/AEI/https://doi.org/10.13039/501100011033), and by the Basque Government through the BERC 2022–2024 program.

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

Declarations

Competing interests The authors declare no competing interests.

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