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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

# Re-evaluating the importance of protein quality: insights on its limited role in multi-nutrient functional units

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## Abstract

**Purpose** Changes in the consumption of protein-rich foods are needed due to their high environmental impacts. However, proteins are indispensable for human nutrition, and there is notable variation in the protein quality of protein-rich foods. The methods to consider protein quality in Nutritional Life Cycle Assessment (nLCA) are still developing. In this study, we assessed the impact of including protein quality in single- and multi-nutrient nutritional functional units (nFUs) in an LCA of products and meals.

**Methods** We conducted an LCA with four different nFUs: protein content, protein content adjusted for protein quality, nutrient index for protein-rich foods, and the same nutrient index adjusted for protein quality. To assess the protein quality of the food products Digestible Indispensable Amino Acid Score (DIAAS) was used. The assessed food products were patties with beef, pork, chicken, trout, perch, chickpea, and soymeal as the main ingredients. The assessments were also done at meal-level, including a side dish of potatoes and mixed salad.

**Results and discussion** Animal-based foods were of higher protein quality. When protein quality was included in the single-nutrient nFU, i.e. protein content, in nLCA, the climate impact decreased for animal-based products and increased for plant-based products. At meal-level, the trend was similar; however, the overall protein quality of meals was lower in comparison to the patties. When including protein quality correction in the nutrient index, there were little to no changes in the index score, resulting in little to no difference in the climate impact.

**Conclusions** Protein-rich foods vary in protein quality, and thus, adjusting protein content with protein quality in nLCAs might be of interest when assessing only one nutrient, i.e. protein. However, we recommend it as an additional measure as there are notable limitations in assessing protein quality. Instead, when assessing multiple nutrients, as in nutrient indices, adding digestibility of protein into the index might not bring additional value to nLCA.

**Keywords** NLCA · Protein-rich foods · Protein quality · DIAAS · Nutrient index · Sustainable nutrition

## 1 Introduction

Nutritional Life Cycle Assessments (nLCA) consider the nutritional aspects, including nutritional quality and health impacts, and the environmental impacts of agricultural

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products and food items (McLaren et al. 2021). Food items can have multiple different functions from providing pleasure to defining culture, but the fundamental function of a food item is to supply adequate nutrition (McLaren et al. 2021). Traditionally, LCA studies on foods have mostly based the environmental impacts on the mass or volume of the food. However, there is substantial variation in the nutrition provided by different food items per a mass unit or a volume unit, and regardless of the other functions of food, nutrition is the most fundamental of them. Therefore, it is of relevance to include nutrition in LCAs (Saarinen et al. 2017). The functional unit (FU) in nLCA can be, for example, a quantity of a nutrient or multiple nutrients, a nutrient density value, or a quality-corrected quantity of a nutrient or nutrients (McLaren et al. 2021).

Proteins are an indispensable part of human nutrition as they are the main dietary source of nitrogen and essential amino acids (FAO 2013). Particularly balanced and sufficient intake of indispensable amino acids (IAA) is needed to ensure the maintenance and growth of body tissues. Adequate intake of high-quality protein is especially important for vulnerable population groups such as infants and children who need protein also for tissue growth and the elderly to maintain cognitive capacity and tissue strength and performance (FAO 2013). In general, in developed countries, protein intake is currently sufficient or even higher than needed, and a variety of protein sources ensures adequate protein quality as the versatile protein sources complement each other (Katz et al. 2019). However, there are population groups also in developed countries, such as the elderly, for whom it is of relevance to pay attention to protein intake and quality. Furthermore, in developing countries, inadequate and unbalanced protein intake remains a significant public health challenge. At the same time, animal-based foods representing major protein sources in many food cultures play a significant role in causing adverse environmental effects (Clark et al. 2022; Davis et al. 2016; Poore and Nemecek 2018). Therefore, focusing on protein in a nLCA is justified.

As protein sources differ in protein quality, it has been proposed to also assess protein quality in addition to quantity in nLCAs (Green et al. 2021; McAuliffe et al. 2023; McLaren et al. 2021). Protein quality can be defined by the amino acid composition and the digestibility of the indispensable amino acids (IAAs) considering the IAA requirements of the target population group (Adhikari et al. 2022). Currently, it is recommended by FAO to use the Digestible Indispensable Amino Acid Score (DIAAS) to evaluate protein quality in human nutrition (FAO 2013). In DIAAS, the level of each digestible IAA is compared to a reference protein, and the lowest value is considered as the score. The reference protein in DIAAS combines the requirements for the IAAs containing all IAAs at the required level per gram of protein based on 100% digestibility (FAO 2013). A score of over 100% provides also the limiting amino acid (LAA) in required levels, and thus, a protein source is considered excellent (FAO 2013). The digestibility in DIAAS is determined at ileal level for each individual amino acid. This is considered more accurate than faecal digestibility which is used in the previously recommended Protein Digestibility-Corrected Amino Acid Score (PDCAAS).

Another aspect to consider when studying protein sources is the possible complementary function of different protein sources at the meal-level. The IAA content of different protein sources can complement each other and so improve the protein quality (Adhikari et al. 2022). Protein utilisation happens in a relatively short time frame, within a few hours after consumption, and during that time, all the IAAs need to be present for maximal utilisation. Therefore, meal-level assessment when regarding protein sources is of relevance instead of diet-level assessments. It has been argued that nLCA studies should also discuss protein quality at the meal-level rather than just at the product level (McAuliffe et al. 2023).

The provision of amino acids is not the only nutritional role of protein-rich foods as they also provide micronutrients. Therefore, it has been recommended that also other nutrients would be considered when studying the environmental impacts of protein-rich foods (McAuliffe et al. 2023; McLaren et al. 2021; Saarinen et al. 2017). To consider several nutrients and, thus, to assess a protein source more holistically, a nutrient index including several nutrients can be used as a FU (McLaren et al. 2021). Product group-specific indices for protein-rich foods can include, for example, the nutrients provided by typical protein sources in addition to the protein content (Green et al. 2021; Kovanen et al. 2024; Kyttä et al. 2023a; McAuliffe et al. 2018; Saarinen et al. 2017; Sonesson et al. 2019). However, these indices have not considered protein quality, which has been considered as a limitation (Kyttä et al. 2023a).

In this study, we evaluate the previous recommendations by Saarinen et al. (2017) and Kyttä et al. (2023a) to consider protein quality in multi-nutrient nFUs, i.e. nutrient indices used as FU, and recommendations by McAuliffe et al. (2023) to consider the IAA provision of the protein sources also at the meal-level. These dimensions are explored through a case study of patties and meals, upon which recommendations for future nLCA studies of protein-rich foods are drawn.

## 2 Materials and Methods

In this study, we conducted a nLCA with three different approaches to consider protein quality, including using single-nutrient nFUs at product-level, multi-nutrient nFUs at product-level, and single-nutrient nFUs at meal-level, and compared the quality-corrected results with those considering only protein quantity. We assessed different home-made patties (i) using the protein content as the nFU, (ii) using the quality-corrected protein content as the nFU, (iii) using a nutrient index as the nFU to consider also the provision of other nutrients, and (iv) using protein quality correction in a nutrient index as the nFU. At meal-level, we assessed complete meals (i) using the protein content as the nFU and (ii) using the quality-corrected protein content as the nFU to evaluate how the other meal components affect the protein quality.

We applied the DIAAS and climate impact calculations on seven different patty recipes. The proteins used for the patties were beef, chicken, pork, trout, perch, chickpea, and soymeal. For detailed recipes, see Kyttä et al. (2023a;2023b). Patties made of pulled oats were excluded due to lack of available data on the amino acid content and digestibility. Some modifications were also done to the recipes due to the lack of available digestibility data, so all the spices and herbs were excluded from the DIAAS calculations, as well as lemon from the trout patty recipe and soy sauce and potato starch from the soymeal patty recipe. The test meals consisted of 50 g of home-made patties, 60 g of boiled potatoes, and side salad of 50 g of lettuce, 20 g of tomato, and 20 g of cucumber. The ratios of different meal components were planned to reflect the Finnish plate model for a balanced meal (Finnish Food Authority 2019). The protein sources for the patties as well as the side dishes were chosen accordingly to typical Finnish food consumption, for example, potato is the most consumed ingredient as a source of carbohydrate (THL 2018).

### 2.1 Calculation of protein quality

DIAAS was chosen as the method to assess the protein quality of the products as it is the method currently recommended by FAO (FAO 2013). The DIAAS value was calculated as follows:

DIAAS % = 100 × [(mg of digestible dietary indispensable amino acid in 1 g of the dietary protein) / (mg of the same dietary indispensable amino acid in 1 g of the reference protein)] (FAO 2013). In this study, the used reference pattern for the reference protein was the age-group of older children (> 3 years), adolescents, and adults. For DIAAS, over 100 capping was not applied, since our study assesses foods and meals instead of complete diets, and hence, there is no over accumulation risks with amino acids.

The US Department of Agriculture FoodData Central (USDA 2023) was used to obtain the amino acid content and protein content data of each food item due to the lack of Finnish data. The data for the true ileal amino acid digestibility (TIAAD) was obtained from previous literature with preference on food products as similar to those on the recipes used in this study with most available data (Bailey et al. 2020b, 2020a; Baker and Stein 2009; Ciuris et al. 2019; Gilani et al. 2012; Kashyap et al. 2018; Rojas et al. 2022; Shaheen et al. 2016). More detailed information for the reference TIAADs per food item are presented in the supplementary material (Table S1).

### 2.2 Nutrient index

The baseline nutrient index (NR-FIprot) for protein-rich foods, created by Kyttä et al. (2023a) and partially validated by Kårlund et al. (2024), was chosen as the nutrient index for this study as it was found to provide relevant sustainability information as a nFU for sustainable choices in the current Finnish food culture. The nutrient index is based on the current Finnish consumption patterns, and it includes nutrients that are provided by the main protein sources in the current diet, hence capturing the nutritional impacts of changes from current consumption to other products, such as plant-based protein-rich foods. The NR-FIprot index includes total of ten beneficial nutrients. In addition to protein, the nutrients are calcium, iron, selenium, zinc, vitamin B6, vitamin B12, niacin, riboflavin, and thiamine.

The nutrient indices used as the nFU were calculated using the same formula by Fulgoni et al. (2009) as in previous studies (Saarinen et al. 2017; Kyttä et al. 2023a, b):

$$NR - FIprot = \sum \frac{NUTRIENTi}{DRIi} \times 100/10,$$

where *nutrienti* is the amount of a nutrient in 100 g of food and *DRIi* is the recommended daily intake (VRN 2014). The nutrient index scores were calculated separately for all population groups, which have separate DRI in the Finnish nutrition recommendations (VRN 2014): 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. No capping at the DRI was used. The index score is presented as a population weighted average. To include the protein quality in the nutrient index, the protein content was corrected by the DIAAS value.

### 2.3 Life cycle assessment

The climate impacts (kg $CO_2$ eq) of the patties were obtained from Kyttä et al. (2023a). Further, the climate impact of boiled potatoes and side salad was calculated as described by Kyttä et al. (2023b). The nFUs were modified for the purpose of this study. The nFUs were the following: protein content (g), protein content corrected with DIAAS, and NR-$FI_{prot}$ nutrient index with protein content and protein content corrected with DIAAS. The climate impact per 100 g protein including the correction with DIAAS was calculated as follows:

$$Climate\ impact\ per\ 100\ g\ DIAAS\ corrected\ protein\ = \frac{kg\ CO_2\ eq}{protein\ \frac{g}{100\ g} \times \frac{DIAAS}{100}} \times 100$$

## 3 Results

### 3.1 Protein contents and limiting amino acids

For the protein content (g/100 g), trout patty had the highest amount of protein with 21.9 g/100 g and chickpea patty the lowest with 5.5 g/100 g (Table 1). The other patties ranged between 11.0 and 18.4 g/100 g. The protein content of the meals followed the same order as for patties, with the protein content ranging between 2.4 and 6.5 g/100 g (Table 2). For comparison purposes, the protein content of meals was also presented as grams per 100 g, containing 25 g of home-made patties, 30 g of boiled potatoes, and 45 g of side salad. Hence, for the entire meal of 200 g, the protein content would be doubled. The LAA for all patties, except pork, was valine (Table 1). For pork, the LAA was leucine. For meals, there was more variation for the LAA, but it was still valine or leucine; except for the meal with chickpea patties, it was sulphur-containing amino acids (SAA) (Table 2).

### 3.2 Protein quality and climate impact of patties by DIAAS

There was some variation in the protein quality of the different patties when analysed by DIAAS (Table 1). For all animal-based patties, the score was over 100% and in a similar range with each other. The highest score was for the pork patty, followed by beef and trout, and then perch and chicken. The lowest score was for the chickpea patty. The score of soymeal patty, although lower than of the animal-based patties, was close to 100%.

The climate impact (kg $CO_2$ eq/100 g protein) of beef patties was considerably higher than that of other products assessed, regardless of whether corrected or not for protein quality with DIAAS (Fig. 1). The second highest climate impact was for chickpea patties, also noticeably higher than for the remaining products. The lowest climate impact was for perch patties, closely followed by trout and soymeal. Pork and chicken patties placed between soymeal and chickpea. The difference in the climate impact between the highest, beef patties, and the lowest, the patties made of the fishes, was remarkable. For beef patties, the climate impact was 19.26 kg $CO_2$ eq/100 g protein without DIAAS and 16.05 kg $CO_2$ eq/100 g protein with DIAAS. For the

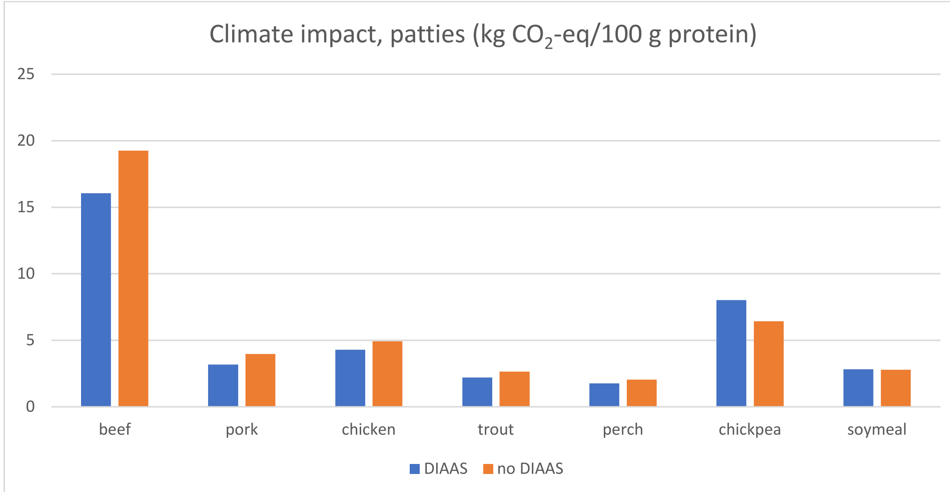
**Table 1** Protein content per 100 g of patty, DIAAS, LAA, climate impact without DIAAS per 100 g protein, and climate impact with DIAAS per 100 g protein for patties

| | Protein (g/100 g of patty) | DIAAS (%) | Limiting amino acid | Climate impact no DIAAS (kg $CO_2$ eq /100 g protein) | Climate impact DIAAS (kg $CO_2$ eq/100 g protein) |
|---|---|---|---|---|---|
| Beef | 15.1 | 120 | Valine | 19.26 | 16.05 |
| Pork | 15.4 | 125 | Leucine | 3.98 | 3.18 |
| Chicken | 11.0 | 115 | Valine | 4.93 | 4.28 |
| Trout | 21.9 | 120 | Valine | 2.65 | 2.21 |
| Perch | 18.4 | 116 | Valine | 2.05 | 1.77 |
| Chickpea | 5.5 | 80 | Valine | 6.42 | 8.03 |
| Soymeal | 13.5 | 99 | Valine | 2.79 | 2.82 |

**Table 2** Protein content per 100 g of meal, DIAAS, LAA, climate impact without DIAAS per 100 g protein, and climate impact with DIAAS per 100 g protein for meals containing the patties, potatoes and a side salad

| | Protein (g/100 g of meal) | DIAAS (%) | Limiting amino acid | Climate impact no DIAAS (kg $CO_2$ eq/100 g protein) | Climate impact DIAAS (kg $CO_2$ eq/100 g protein) |
|---|---|---|---|---|---|
| Beef | 4.8 | 110 | Valine | 18.00 | 16.36 |
| Pork | 4.9 | 110 | Leucine | 6.04 | 5.49 |
| Chicken | 3.8 | 104 | Leucine | 7.30 | 7.02 |
| Trout | 6.5 | 114 | Valine | 4.40 | 3.88 |
| Perch | 5.6 | 108 | Leucine | 4.19 | 3.88 |
| Chickpea | 2.4 | 76 | SAA | 9.53 | 12.54 |
| Soymeal | 4.4 | 94 | Valine | 5.35 | 5.69 |

**Fig. 1** Climate impact (kg $CO_2$ eq/100 g protein) of patties with and without correction for protein quality with DIAAS



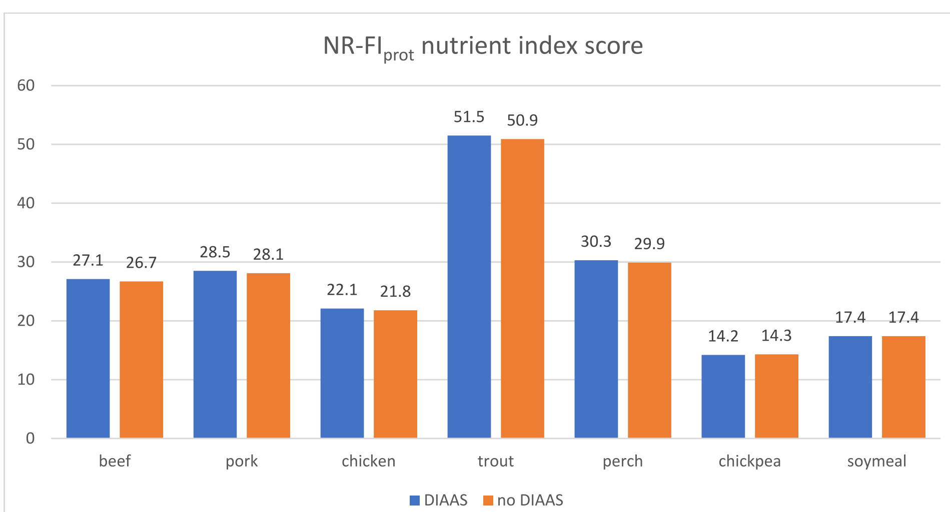

fishes, the climate impact averaged as 2.35 without DIAAS and 1.99 with DIAAS, so the climate impact of beef patties was over eight times higher than for the fish patties. For the other red meat alternative, pork patties, the difference in climate impact with the patties made of fish was considerably smaller, yet 60–70% higher depending on the inclusion of DIAAS.

For animal-based products, correcting for protein quality with DIAAS decreased the climate impact, and for plant-based products, the correction increased the climate impact. For beef patties, the absolute decrease was the largest, while for the other animal-based patties, the decrease was a lot smaller, being similar to the uncorrected climate impact. However, the percentage decrease was the largest for pork with 20% decrease, while for the other animal-based patties, the decrease of climate impact was between 13 and 17%. For the chickpea patties, the absolute increase in climate impact was also higher, although not as high as the decrease for beef patties. Yet, the percentage increase was larger for chickpea patties with 25% increase in climate impact compared with the 17% decrease for beef patties. As the DIAAS for soymeal patties was close to 100%, the climate impact increased only 1% when corrected for protein quality.

### 3.3 Nutrient index score and climate impact

Correcting for protein quality with DIAAS made little to no difference in the NR-$FI_{prot}$ nutrient index score in any of the studied products (Fig. 2). For animal-based products, the index score was somewhat higher when corrected for protein quality with DIAAS. For chickpea, the score was lower, but there was no difference for soymeal score. Overall, the highest index score was for trout, followed by perch. The lowest scores were for the plant-based products.

**Fig. 2** The NR-$FI_{prot}$ nutrient index score of patties with and without correction for protein quality with DIAAS



The climate impact (kg $CO_2$ eq/index) was the highest for beef patties (Fig. 3). The other products were relatively similar in climate impact and considerably lower than beef patties. Fish-based products had the lowest climate impact. The climate impact of the beef patties was over nine times higher than of the fish-based patties. Pork patties averaged with the same climate impact as soymeal patties, resulting as the third and the fourth lowest climate impact. There was only minor difference in the climate impact when the protein content was corrected for protein quality with DIAAS. For animal-based products, there was a decrease of 0.9–1.6% in the climate impact with DIAAS. For chickpea, the correction increased the climate impact 0.8%. For soymeal, there was no difference.

### 3.4 Protein quality and climate impact of meals by DIAAS

There was some variation in the protein quality of the meals with different patties (Table 2). The DIAAS for all meals with animal-based patties was over 100%, whereas for the meals with plant-based patties, it varied between 76 and 94%. The highest score was for the meal with trout patty, followed by beef and pork. The lowest score was for the meal with chickpea patty.

The climate impact (kg $CO_2$ eq/100 g protein) was highest for the meal with beef patty whether or not corrected for protein quality (Fig. 4). The second highest climate impact was for the meal with chickpea patty, also relatively higher than for the other meals. The lowest climate impact was for meals with trout and perch patties, closely followed by the meal with soymeal patty. Again, when the protein content

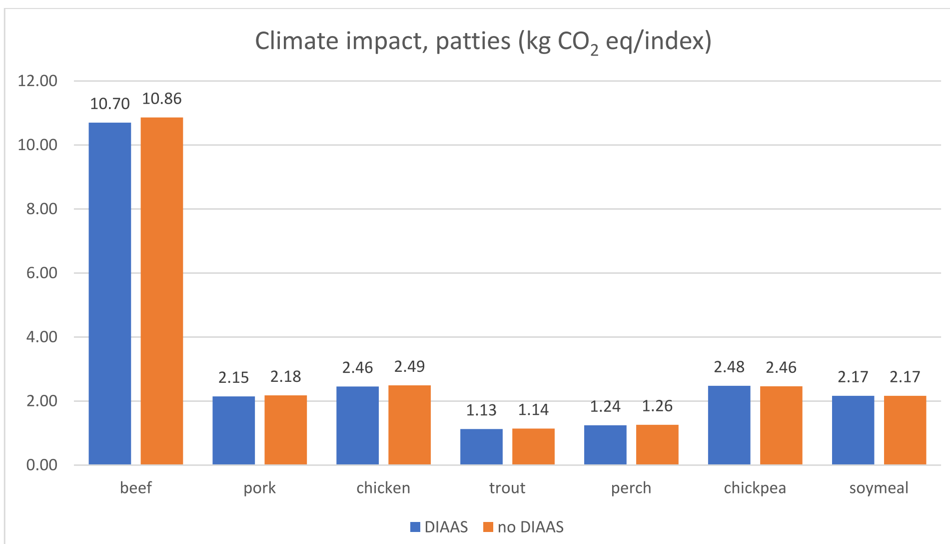



**Fig. 3** Climate impact (kg $CO_2$ eq/index) of patties with and without correction for protein quality with DIAAS in the index

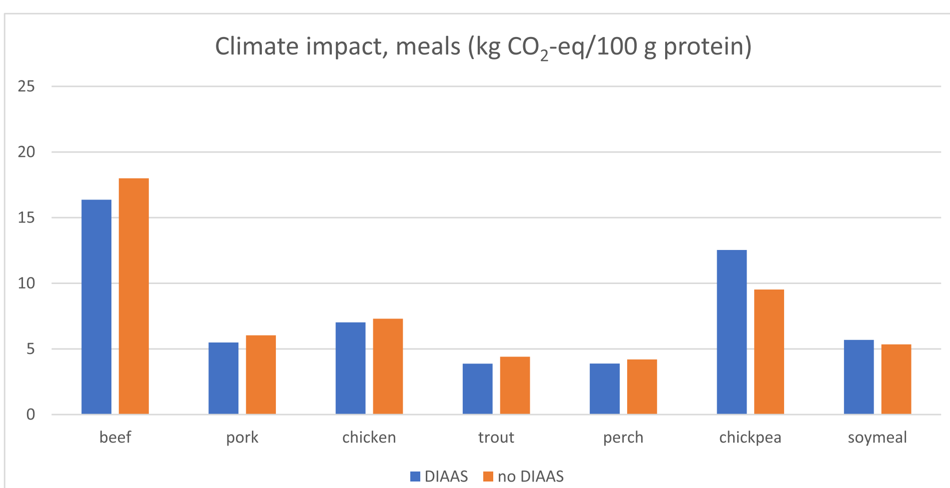



**Fig. 4** Climate impact (kg $CO_2$ eq/100 g protein) of meals with and without correction for protein quality with DIAAS

was corrected for protein quality with DIAAS, the climate impact of the meals with animal-based patties decreased and for the meals with plant-based patties increased. This did not change the order of the meals, except trout and perch had the same climate impact when corrected with DIAAS. For meals with beef and chickpea patties, the absolute difference in the climate impact with and without DIAAS was considerably higher than for the meals with other patties, the meal with chickpea patties having the highest difference with a 32% increase in climate impact when correcting for protein quality with DIAAS. However, the highest percentage decrease in climate impact when corrected with DIAAS was for the meal with trout patties with a decrease of 12%.

## 4 Discussion

This study addressed many of the aspects that were considered as limitations in previous studies focusing on nLCA (Kyttä et al. 2023a; McAuliffe et al. 2023; McLaren et al. 2021; Saarinen et al. 2017). We included protein quality when studying the climate impact of protein-rich foods and used the currently recommended method, DIAAS, to assess it. In this study, protein quality was also included in a nutrient index that considers the provision of multiple nutrients alongside protein content. The assessment was also done at meal-level, which has also been recommended for future nLCA studies (McAuliffe et al. 2023). To our knowledge, the protein quality corrected indices and meal-level assessments have not been implemented in previous nLCA studies.

### 4.1 Protein quality and the impact of protein quality correction on climate impact

The results regarding the protein quality of the different food products were in accordance with previous studies (Adhikari et al. 2022; Mathai et al. 2017; Tomé 2013): animal-based products are of higher protein quality than plant-based products, and of plant-based products, soy-based products perform well with a DIAAS value of over 90%. It was expected to get similar results as published previously, as the true ileal digestibility values used to calculate the DIAAS were gathered from previous literature. Plant-based protein sources tend to perform worse due to their poorer IAA composition which has the most influence on the DIAAS value (Herreman et al. 2020). In addition to poorer IAA composition, low ileal digestibility can also impact DIAAS values. This affects especially plant-based proteins for multiple reasons, including the LAA of the protein, protein secondary conformations, and other compounds present in the protein sources. Nevertheless, there is a great variation within plant-based proteins, and both plant-based products studied in this study, soymeal and chickpea, resulted as high-quality proteins with a DIAAS above 75. However, it is to be noted that digestibility does not definitively indicate the protein utilisation which is due to the losses that happen during protein digestion (Itkonen et al. 2024). Still, the high-quality results of plant-based products are valuable as the current food production and consumption threatens both environmental sustainability and human health, which is mostly due to the unsustainable consumption of animal-based proteins (Willett et al. 2019). Thus, the need to transform food production and diets affects especially the protein sources in the diet, and the shift to more plant-based diet requires more attention to protein quality.

Including the protein quality correction when assessing the climate impact resulted in the following pattern: for animal-based products, the climate impact decreased, and for plant-based products, the climate impact increased when incorporating DIAAS. This was due to the DIAAS value of over 100% for the animal-based products. As the soymeal patty had a DIAAS value of 99%, the change was small when comparing the climate impact with and without DIAAS. Overall, even though there was a small change when including the protein quality, the change did not affect the order of how the products ranked. However, if a lower quality plant-based protein source would have been included in the study, it is possible that it could have affected the ranking of the products as the lower the DIAAS value is, the larger is the increase of climate impact. It is not straightforward to compare previous nLCA studies that have used protein quality as a nFU as the methodologies differ. However, there has been similar findings regarding the effect of applying a protein quality nFU on animal-based and plant-based products. In general, including protein quality has brought the climate impact of animal-based and plant-based products closer to each other (Draijer et al. 2023; McAuliffe et al. 2023; Sonesson et al. 2017). Here, we studied only the climate impacts, but also, in other impact categories, the relative differences between the products would change similarly in magnitude, as the reference flow per unit of index score remains consistent across all impact categories.

### 4.2 Including protein quality in a nutrient index

In the NR-FI$_{prot}$ nutrient index, protein is only one of the many nutrients assessed, which resulted in little to no difference in the index score when including the protein quality correction. Yet, the limited inclusion of bioavailability of the different nutrients in nutrient indices has been previously considered as a limitation (Kyttä et al. 2023a). However, this study shows that the inclusion of the digestibility of protein does not seem to have a significant impact on the results, thus demonstrating no additional value when multiple nutrients are considered. As there was little to no change in the index score itself when including protein quality, there was also little to no change in the climate impact regardless of whether the nutrient index as a nFU included the adjustment for protein quality or not. It seems that the contribution of one nutrient in a nutrient index where multiple nutrients are considered is so insignificant that it does not affect the final score. Also, there is uncertainty related to the environmental impacts, nutrient composition, and DIAAS, and thus, the differences seen in the results might also originate from the underlying uncertainties. Therefore, applying protein correction in an nLCA study may be just an apparent refinement to otherwise uncertain results. However, different nutrients can differ largely in terms of their digestibility, bioaccessibility, and bioavailability. Therefore, it is possible that the inclusion of the bioavailability of other nutrients than protein could have greater impact on the score, as demonstrated in terms of iron by Kyttä et al. (2023a), and hence, it would be of interest to include the bioavailability, or bioaccessibility, of all the nutrients in future research.

## 4.3 Comparing patties and meals

For most parts, when comparing the patties and the whole meals including the same patties, the results had similar patterns and followed similar orders. As the meals were not planned for optimal or maximal protein content or quality, but based on typical Finnish consumption patterns, the protein content was considerably lower for entire meals than patties only per 100 g. The potatoes and the side salad reduced the overall protein content of the meals; yet, it offers a more realistic picture as foods are typically consumed as meals, and often the side dishes are of lower protein content.

As expected, also the protein quality was lower for the meals when compared to the patties. This is because the side dishes such as vegetables are of much lower protein quality, with a DIAAS of 57% for the whole side dish, including the potatoes and the salad. It is noteworthy that another choice for the source of carbohydrates could have complemented the IAA composition better, e.g. the meal with chickpea patties would have likely scored better with a grain-based side dish, such as pasta or bread, as the amino acid composition of legumes and grains complement each other and, thus, improve the overall protein quality (Fakiha et al. 2020). When comparing the protein quality of the patties and the meals, the order between the products slightly changed, as the highest DIAAS of patties was for pork, but for meals, it was for trout patty. This is because of the different amino acid compositions and different LAAs. For the side the LAA was leucine, the same as for pork patty. However, for trout patty, the LAA was valine, and therefore, it complements the side and improves the DIAAS of the meal. The difference in the score was smaller for the products with plant-based protein sources. This could be due to the initially lower score of the plant-based patties, which was closer to the score of the side dish.

The LAA changed for three patties when comparing just the patties and the meals with the same patties. Presumably, this is due to the small enough difference between the first LAA and the second LAA, so the amino acids present in the lowest and second lowest amounts. For chicken and perch, the LAA of the patty was valine, but for the meal, the LAA was leucine. Leucine is both the LAA of the side dish and the second LAA of both patties. The chickpea patty and the side dish had the same second LAA, i.e. SAA, so explaining the change of LAA to SAA for the meal.

The climate impact of the meals was higher than of the same patties with and without DIAAS, except for one meal. This is likely due to the overall lower protein content of the meals, as the protein content of a product affects largely the climate impact. Only the meal with beef patty had a lower climate impact than just the beef patty, and only when the nFU was the protein content without adjusting for protein quality with DIAAS. This could be due to the very high climate impact of the beef patty which the side dishes reduce proportionally more in comparison to the other products. The meals ranked in the same order as the patties both with and without DIAAS. Just the meals with fish-based patties had the same, lowest, climate impact when the protein content was adjusted with DIAAS, compared to the patties for which the perch patty had the lowest climate impact closely followed by trout patty. As expected, the inclusion of protein quality with DIAAS resulted in same pattern as for the patties: the climate impact of meals with animal-based patties decreased, and the climate impact of meals with plant-based patties increased.

Even though the meal-level assessment hardly affected the order how the products ranked regarding the protein quality or climate impact, it shows that there is an additional value in meal-level assessments. The meal with chickpea patty highlights this as the climate impact increases considerably at meal-level, and especially when the protein quality is also included. It brings the climate impact relatively close to the climate impact of the meal with beef patty which was much further away from when assessing the product-level, i.e. only patties. However, as the result is largely due to the low protein content and quality of the chickpea patty and the meal, it is likely that another choice of side dishes could lead to a better result as previously discussed.

## 4.4 Future research needs

Even though DIAAS is currently the recommended method for assessing protein quality, there are limitations in the use of it, mostly regarding the availability of data which is still quite limited. The benefit of DIAAS in comparison to the previously widely used method (PDCAAS) is that it uses true ileal digestibility values instead of more unreliable faecal values. It is preferred to determine the ileal digestibility in humans (FAO 2013). However, acquiring this human data is complicated, and thus, often the available data is from animal models. The limited availability of data remains as a challenge still when including all possible data on ileal digestibility and often compromises had to be done (McAuliffe et al. 2023). Thus, for more accurate use of DIAAS, there is a need for a more detailed TIAAD values for a wider variety of food products with a focus on everyday food items. However, ileal digestibility whether from humans, pigs, or rats is still preferred over faecal digestibility, supporting the use of DIAAS instead of PDCAAS.

There has also been a discussion whether nutrient metrics should be capped or uncapped, and for studies on diet or food supply, capped values are recommended (Green et al. 2023). For foods, uncapped values can be used, but risks, for instance, the overaccumulation of the nutrient in question should be considered. For protein and amino acids, the overaccumulation is not a risk, and the amino acid profiles of different food items can complement each other. As this study was done also at meal-level, it was of relevance to use uncapped DIAAS values to include the possible complementarity of different food items. However, it is arguable whether uncapped values should be used in a nLCA as DIAAS values of over 100 do not result in better nutritional value, and thus, it does unnecessarily favour animal-based products. Therefore, it could be of relevance to consider the use of capped values in future studies.

The DIAAS values also include uncertainty (e.g. Herreman et al. 2020), which means that in LCA, there is an uncertainty both in the environmental impacts themselves and in the functional unit. Therefore, future research should also consider ways to address the uncertainty present in nLCAs.

Other area of interest for future research is expanding the meal section of the study. A wider variety of side dishes and protein sources would offer better view on the complementarity of different protein sources and a more realistic representation on the variety of diets. As the studied food products were typical of Finnish food culture, it is representative of a developed country in which the intake of good-quality protein is typically quite high (Katz et al. 2019). Therefore, it would be relevant to study the effect of adjusting protein content for quality with DIAAS on climate impact with typical food products and meals for developing countries. Diets in developing countries are often based more on plant-based foods which are of lower protein quality (de Vries-Ten Have et al. 2020) and, so, could have a larger effect on climate impact. It would be also of interest to apply a nutrient index on whole meals. However, it creates a new challenge of choosing a suitable nutrient index. The inclusion of the bioaccessibility of all the nutrients of a nutrient index is yet another interesting but challenging aspect for future research.

Here, we have considered the nutrition through using nutritional functional units, but another approach used in nLCA is to assess the health impacts resulting from the consumption of the food (Scherer et al. 2024; Stylianou et al. 2021). The current health impact assessment method is not able to consider the protein quality, but future research is needed to explore which aspects should be regarded as functions and which should be assessed as impacts, as well as how these two approaches could complement each other.

## 5 Conclusions

Adjusting protein content with protein quality in nLCAs might play an important role when assessing only one nutrient, i.e. protein, especially when comparing animal- and plant-based foods. It is of relevance to consider the protein quality at meal-level to include the possible complementarity of protein sources. However, protein-rich foods also provide several other nutrients, and therefore using broader set of nutrients as the functional unit more comprehensively captures the nutritional function of foods. As demonstrated here, including protein quality when considering multiple nutrients in the nFU does not profoundly affect the results. Thus, it is arguable if adding protein quality correction in multi-nutrient nFUs brings additional value to a nLCA, which typically has high uncertainty stemming from the underlying data. As assessing the protein quality also faces notable limitations due to availability of data, we recommend handling the protein quality as an additional measure to protein content when assessing only protein, and as a separate measure from multi-nutrient nFUs, until more comprehensive approaches for considering bioaccessibility of different nutrients is available. Further research is also needed to evaluate how bioaccessibility should be considered in product, meal, and diet level assessments.

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**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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