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System expansion is needed to handle the multifunctionality of food items in environmental impact assessment

Ilkka Leinonen[1]✉, Pasi Korkalo[2], Sanna Hietala[3], Kirsi Usva[4] & Merja Saarinen[4]

Any comparison of the environmental impacts of different food items should be based on their functionality, such as providing nutrients and energy. In this study, a Life Cycle Assessment (LCA) approach was developed for quantifying the Global Warming Potential of different protein sources. This approach is based system expansion, which, according to the LCA standards, is a preferred method for handling multifunctionality, but still largely ignored in nutritional LCA so far. The method makes it possible to compare different individual food items based on their function in human nutrition. In this case study, the provision of balanced amino acids was selected as such a function, and provision of energy for metabolic process was handled as a "by-product". This new approach reinforces the current methodology of nutritional LCA and improves its ability to compare the environmental performance of different food items with partially different functionality.

Animal based foods have a high contribution to global greenhouse gas emissions. The reduction of such emissions is possible for example by exchanging food products with a high environmental impact (e.g. animal based) with those that have a lower environmental impact (e.g. plant based). Understanding the impact of such product exchanges for marginal dietary shifts requires the identification of the environmental impact of individual food items. The product level assessment of environmental impacts can also help food producers to mitigate the environmental footprint of their products[1–4]. Recently, in addition to assessing the environmental impacts, more attention has also been paid to the nutritional adequacy of food[5–10].

The Life Cycle Assessment (LCA) framework is an established method for assessing the environmental impacts of food products. When applied at the diet level, it is possible to directly compare the environmental impacts of different combinations of food items that fulfill certain nutritional requirements. However, comparing the environmental impacts of single food items while also considering the nutritional quality of these items is not as straightforward[11]. Despite the methodological complexity, such a comparison is needed, as choices of single products also determine the properties of the diet, including its environmental impacts. Quite often the comparison between food items has been done using mass-based or volume-based units (e.g. one kilogram or one liter of the product). Although in the LCA terminology the mass or volume units can be considered to represent the reference flow of the production system, they do not represent the functionality of food, and therefore, in most cases, cannot be used as functional unit that would allow justified comparison between different items. However, lately the nutritional aspects have been addressed in a methodological development of food LCA, under a concept called a nutritional LCA, or nLCA, which aims to integrate the nutrition, health and environmental assessments of food[11].

A starting point of the LCA is the definition of the "functional unit" (FU), i.e. "the quantification of the identified functions (performance characteristics) of the product". For diets, one of the main functions can be defined as provision of the energy and nutrition required by a human, given that many other possible functions can also be considered. In contrast, for single food products, this is not the case, as basically every single food item can have a different function. Some of them may provide energy, some certain nutrients, some may be consumed only because of their taste. Therefore, finding a single FU fit for every food item is, by definition, not possible. Instead, the FU should reflect the main function (e.g. provision of protein) of a certain group of food items, but also in that case, the multifunctionality should be taken into account in the assessments.

[1]Natural Resources Institute Finland, Latokartanonkaari 9, 00790 Helsinki, Finland. [2]Natural Resources Institute Finland, Ounasjoentie 6, 96200 Rovaniemi, Finland. [3]Natural Resources Institute Finland, Paavo Havaksen Tie 3, 90570 Oulu, Finland. [4]Natural Resources Institute Finland, Tietotie 4, 31600 Jokioinen, Finland. ✉email: ilkka.leinonen@luke.fi

In nLCA, a 'nutritional functional unit' (nFU) has been suggested to be specified aiming "to provide a common unit of analysis for standardising comparative nLCA of alternative food items"[12]. Recently, nFU has been applied based on the nutrient indices[13] for either all kinds of food products[8,14–16] or for a specific product group[8–10,17]. Protein sources are a product group often addressed in nFU developments, which is rational as the variation of environmental impacts is the largest in this product group[10]. However, even if the protein intake is included in the nutrient index, that does not necessarily represent a sufficient nutritional function of protein, because the amino acid composition and their digestibility vary between products made from different raw materials. Therefore, the quality of protein, including the concentration of essential amino acids (EAA), should also be considered. Some applications for this have been suggested[12,18,19], but the approach is still evolving.

In spite of the progress in developing the nutritional indices, the problem of comparability still remains. Even if the function of certain food items is seemingly identical (e.g. provision of high-quality protein), each item may have some additional functions, the most important of which can be considered to be the provision of energy that is necessary for human survival. The provision of energy may differ strongly between food items, and the differences in the energy content may often be totally ignored in nutrient-based comparisons.

Despite this apparent complexity related to multifunctionality of food items, the standard LCA methodology provides a consistent framework for handling production systems that produce outputs with multiple functions. Following the LCA standards[20,21], the environmental impacts may be allocated between different functions, but more preferably, the LCA standards recommend avoiding allocation through system separation or system expansion.

Global warming potential (GWP) is a measure of how much heat a greenhouse gas traps in the atmosphere over a specific time period, relative to carbon dioxide, and in LCA studies, GWP is a generally used indicator of the climate warming impact of various products and processes. In LCA, a commonly used unit for the GWP impact category is 1 kg carbon dioxide equivalent (kg CO_2e). In this study, an LCA approach based on system expansion was developed, in order to quantify and compare the GWP of different protein sources. Although prioritized by the LCA standards, it is quite surprising that system expansion has not been generally used in nutritional LCA, or in other LCA analyses focusing on comparison of food items. The method developed here focused on the functionality of protein in human nutrition, i.e. the provision of balanced amino acids. In addition to provision of amino acids, also a "by-product" of the protein sources, namely the provision of energy for metabolic functions, was taken into account in the development of the method. The GWP of different protein sources was determined by applying the LCA methodology as specified in the ISO 14040 standard[20]. The FU of the assessment was determined to be *1% of the daily requirement of a 75 kg adult for all essential and conditionally essential amino acids*, and the reference flow was the amount of a food product that would fulfill this required function. In addition to this main function, an additional function was also considered, namely *the delivery of energy for human metabolic functions*. The idea of this addition is that some protein sources can have a high content of energy, and therefore they can replace other energy sources in human nutrition, and in that way reduce the environmental impacts related to production of those energy sources. To allow the full comparison between different protein sources, fat, or more specifically vegetable oil, was selected as a substituted food item to be included in the assessment. This vegetable oil provides energy that could be partially replaced by the energy contained in the selected food items in the form of fat, carbohydrates and protein. Fat was selected as a substituted energy source because it forms a major component of the energy content of animal-based protein sources. Another option would have been to use carbohydrates as a substituted energy source. However, this would have been problematic, as most sources of carbohydrates (e.g. cereals, root vegetables) contain also protein, and this would have made the comparison between the selected protein sources unbalanced, and in practice, the only food ingredient with pure carbohydrate that could have been included in the analysis would have been white sugar.

Following the principles of system expansion, combinations of the selected protein sources and the substituted "pure" energy source oil were formulated that would cover both functions, i.e. provision of certain amount of essential and conditionally essential amino acids and additional provision of metabolizable energy.

Results

The results show big differences in the amount of each food item needed to fulfill the specified requirement of amino acids (Fig. 1a). This variation is partly due to the different protein contents of these items but also due to the very different amino acid composition of each protein source.

Of the selected food items, cheese has the highest protein content per unit of mass, and in general, the protein content of the other animal-based food items is also relatively high. In contrast, the legumes and especially liquid milk have much less protein per mass unit. Therefore, in terms of mass, the required consumption of many plant-based food items is generally higher than the animal-based foods (with exception of liquid milk). This is also a general issue when comparing "wet" and "dry" food items. However, this does not create any problems with comparability in LCA, as far as the functionality in the comparison has been selected properly.

The energy content of the protein sources also varied strongly as a result of different contents of fat, carbohydrates and protein, and the highest energy contents were found in nuts and high-fat pork. So, following the principles of system expansion, to achieve equal energy contents of the compared items, variable amounts of vegetable oil were substituted in the case of each of the protein sources (indicated by negative consumption in the Fig. 1a). Amongst the protein sources included in the comparison, the lowest energy content was found in chicken meat, which was therefore selected as the baseline for the comparison. For all other food items, the additional energy content, in comparison to chicken, was quantified and the amount of vegetable oil providing corresponding amount of energy was substituted. As a result, the amount of substituted oil varied from zero (chicken meat) to 0.0033 kg (nuts).

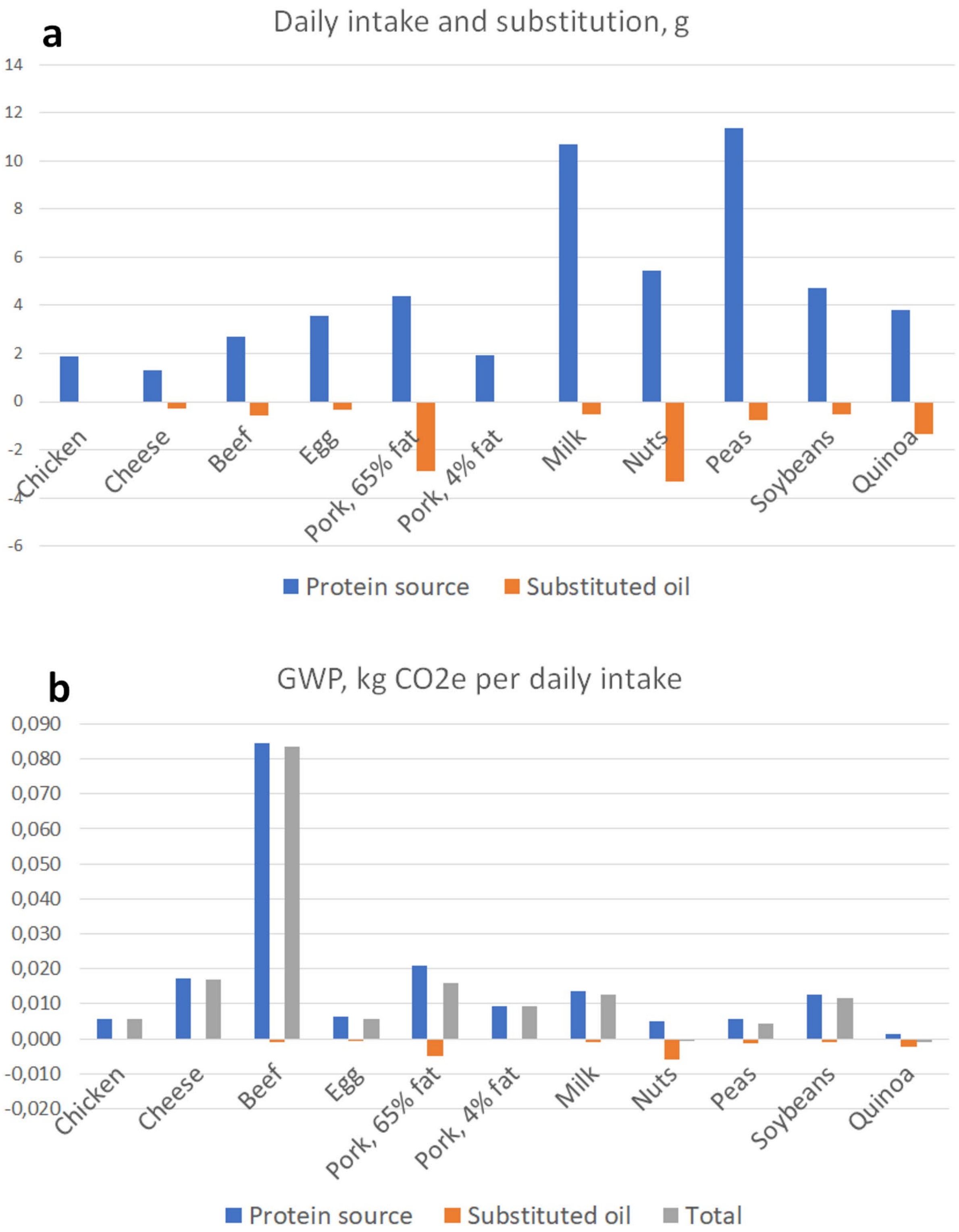

Fig. 1. **a** The intake of each protein source needed for 1% of the daily requirements of all essential amino acids and the substituted amount of vegetable oil. Substitution is shown as negative values. **b** Global warming potential of the combinations of required amount of protein source and the substituted vegetable oil.

The GWP of each of the combinations of protein source and substituted vegetable oil is shown in Fig. 1b. In most cases, the total emissions are dominated by the protein, and the substituted vegetable oil has only a minor, negative contribution to emissions in case of most food items. The highest emissions can be found in some of the animal-based products included in the study, namely beef, high-fat pork and milk products, and most plant-based protein sources had a relatively low GWP. The emissions of beef and milk products are largely related to methane emissions arising from enteric fermentation occurring during the growth cycle of the animals. The reasons for the high emissions of high-fat pork are different. If the meat has high fat content, relatively large amount of meat would be required in terms of mass, in order to provide enough protein to fulfill the specified requirement for essential and conditionally essential amino acids. As this amount of meat is considerably higher than the required amount of for example leaner chicken meat, the emissions are also much higher. The results are clearly different in the case of leaner (4% fat) pork meat where a smaller amount of meat is needed to fulfill the nutritional requirements.

The lowest GWP was found in quinoa, nuts and peas, although the GHG emissions of peas were only slightly lower than those of certain animal-based protein sources. In the case of peas, as a result of the low amount of the sulfur amino acid and the relatively low protein concentration in general, the required amount of peas is several times higher compared for example to meat. However, the carbon intensity per mass unit of peas is much lower than the carbon intensity of many other protein sources included in this study (for example the meat products), and therefore the emissions per unit of the required amino acids remained relatively low. Although the production of nuts generates relatively high emissions per kg of the product, their amino acid concentration is very high and therefore relatively low amounts of this product were needed to fulfill the specified nutritional requirement. Further, the energy content of nuts is also high, so a large amount of oil was substituted in system expansion. For these reasons, the overall emissions per FU remained low.

Amongst the remaining food items, soybeans showed relatively high emissions compared to other plant-based protein sources. The content of the essential amino acids in soybeans is comparable with the animal-based products included in this study. However, the production of soya can be very carbon intensive, if emissions arising from land transformation are included in the analysis. In this study, the Brazilian production data for soya was used in the comparison. So, part of the soya originates from areas where land transformation has occurred, and those emissions are included in the results shown here. As a result, the average emissions for soya are relatively high, and therefore in this study the emissions per the nutrition-based FU are not any lower than those of some of the animal-based product. It should also be noted that soya is a central part of the feed of most non-ruminal animals, so the emissions from land transformation have a contribution also to the emissions arising from the production of chicken meat and pork.

Discussion

Following the basic principles of LCA, the comparison the environmental impacts of different food items should be based on the actual functionality of food, such as the provision of energy and nutrients, which was the case in the present study, not on mass or volume. For example, according to the European Commission Product Environmental Footprint[22] guidelines, the selected FU is the quantified performance of a product system, and the definition of the performance should include the elements "what", "how much", "how well" and "how long". Mass-based or volume-based units usually only specify the element "how much", and, in principle, they could only be used in comparison in cases where all other properties of the compared food items are equal. It is also common to use the energy or protein content of the food as an FU[4], and this can be seen as a step forward in comparison to the total mass or volume of the food item as an FU. However, such a choice still ignores the fact that different proteins can be functionally different, as demonstrated in this study, and it does not handle the issue of the multifunctionality of the food either.

The need for a clearly specified FU is the case also in comparison of products within a specified product group with each other (for example animal products, plant-based products, or protein sources in general), as also within those groups some food items may provide functions that some other items do not provide. In this study, food items that could be classified as "source of protein"[10] were selected for the demonstration of this nutrition-based LCA approach. Amongst the separate functions of the protein sources included in the assessment, the provision of essential and conditionally essential amino acids was considered to be the main function and the provision of energy an additional function. In general, the provision of amino acids and the provision of energy can be considered as by far the biggest drivers of the global food production. Assuming an energy demand of 8000 kJ per person per day, the global population of 8 billion people needs about 23 000 000 TJ of food energy per year. To put into the context of food production, this amount of energy would be equivalent to over 1600 million tons of wheat. Similarly, the global demand for protein, or specifically the demand for certain amino acids, has been previously demonstrated[23]. As a result of such vast demand, the global agricultural land use is currently dominated by four crop species: wheat, maize, rice and soyabeans[24]. Of these crops, wheat, maize and rice are primary grown for carbohydrate production (energy source), while soyabeans are an important source of protein and vegetable oil (energy source). Furthermore, nearly all global animal production is primarily targeted for provision of protein (amino acids) in the form of meat, milk and eggs. Therefore, it can be concluded that also the environmental issues arising from food production and being assessed with LCA are predominantly driven by these two functions.

As discussed by Leinonen et al.[23,25] the differences in the amino acid composition of different protein sources have a big effect of the required amount of each protein source to fulfill the human nutrient requirements. In many plant-based protein sources, lysine is generally the most limiting amino acid. Therefore, even if many cereals can contain a high amount of protein, they are not sufficient to be used as the only protein source in human nutrition as their lysine concentration is generally very low[23,25]. The lysine concentration is higher in legumes such as peas and beans. On the other hand, the concentration of some of the essential, so called sulfur amino acids methionine and cysteine, is relatively low in these food items. In this study, the high amount of peas needed to fulfil the required amount of essential amino acids demonstrates this. At the diet level, a balanced combination of different food items is needed to ensure that the nutrient requirements are fulfilled, and for example protein sources with high content of either sulfur amino acids or lysine can supplement each other. However, when quantifying and comparing the environmental impacts of individual food items instead of the diet level-assessment, a justified comparison between those can only be done if the items are made functionally equal[20,22], as was done in this study.

The results show similar patterns as the study based on the nutritional FU by McAuliffe et al.[12]. The main differences between the studies are related to the comparison between differences of the protein sources. One of the methodological differences between the studies is the selection of the FU. In the current study, the FU was 1% of the required amount of all essential and conditionally essential amino acids, while McAuliffe et al.[12] used 100 g of protein as FU. To avoid the functional differences caused by the protein quality, McAuliffe et al.[12] adjusted their FU by multiplying it by the Digestible Indispensable Amino Acid Score (DIAAS), specific for each protein in consideration. Technically, both solutions are expected to provide similar outcomes, as the DIAAS is also based on the human requirements for essential amino acids. The actual difference between these approaches can therefore considered to be more practical than technical. According to the ISO 14040 standard[20], "the functional unit defines the quantification of the identified functions (performance characteristics) of the product". In our study, this definition of the FU can be considered rather unambiguous: "*1% of the daily requirement of a 75 kg adult for all essential and conditionally essential amino acids*", while the alternative FU, DIAAS-adjusted protein mass, may not be easily adopted by the performer or the utilizer of an LCA study.

The biggest difference between the approaches is, however, the way how other functions of the food items, in addition to provision of amino acids, are handled. The provision of energy is one the most important of such functions, at least as far as only the nutritional aspects of food are considered. In the approach based on the DIAAS protein score, this function is ignored, while in the system expansion-based approach, energy is handled as a by-product. In general, inclusion of such additional functions is probably the biggest problem of the so called nutritional LCA. The starting point in nLCA is usually the inclusion of all relevant functions provided by different nutrients in a single nutritional score. For example, Kyttä et al.[10], selected different nutritional indices for three product groups, namely 1) vegetables, fruits and berries, 2) protein sources, and 3) carbohydrate sources. Although being rather arbitrary, this division can be justified; each of these groups can be considered to have a different nutritional function. However, the problem occurs when these functions overlap. For example, a product being primarily a protein source can also provide carbohydrates or fat (energy sources). In many nLCA studies, the provision of energy has not been included in nutritional index specific for the protein sources and is therefore excluded from the assessment. To include this function, or any other additional functions, expansion of the system under assessment may be necessary also in the case of assessments based on the nutritional indices.

As recognized in the nLCA methodology[10,11], in addition to amino acids, provision of other nutrients (including micronutrients) is also part of the function of some food items. The inclusion of these nutrients in nutritional indices is aiming to improve the comparability between different food items. However, the main question still remains with such an approach: if the intended function of certain food items is not to provide certain micronutrients, how relevant is it to base the comparison on assumption that such nutrients should be part of the FU applied in the assessment? Again, the use of the systems expansion approach could provide a solution for this problem.

In general, the methodology presented here can be considered to capture the functionality of single food items in a more realistic way than methods based on the total mass or total volume of the products, or on their protein or energy content. For example, as shown by McAuliffe et al.[12], methods based only on the total crude protein content of food items are likely to overestimate the environmental impacts of animal-based protein sources and underestimate the impacts of plant-based protein sources when compared to the methods based on more realistic amino acid compositions.

This study focused on the climate impact, as this impact category is generally considered critical in protein production. However, it should be noted that climate impact is not the only environmental concern related to food production, but also impact categories such as eutrophication potential, acidification potential, land occupation, water scarcity footprint and so on are highly relevant[26,27], Unfortunately, the research articles that were used as data sources in this study did not provide enough information to make any systematic comparisons on other environmental impacts except the GWP between the food items. However, the current methodology is fully capable to quantify any other environmental categories as well, providing that full life cycle inventory data on the production system is available.

Inclusion of micronutrients was not part of the comparison carried out in this study. Technically, this could be done in a similar way as the inclusion of the food energy, i.e. handling micronutrients as "by-products" and expanding the system to include additional food items providing those nutrients. In such a case, it may be beneficial to concentrate only on less available nutrients to simplify the analysis. Further, such an expansion would be needed only if there are differences in the content of those critical micronutrients between the food items included in the comparison. In general, however, it should be noted that relatively small amount of such nutrients would be needed, compared to the main nutritional components of food, namely energy and essential amino acids. So, it is quite possible that inclusion of minor nutritional elements in comparison may not have any major effect on the comparison of food items within a certain food category, such as sources of protein in this study. This needs to be confirmed with further analyses.

As a conclusion, this study has provided a potential solution for some inconsistencies that currently still exist in the nLCA methodologies. The nFU can potentially include a large number of nutritional properties to be used as a basis of the assessment. As a result, the provision of these properties is built in the determination of the assessed function of an LCA study, and also in the determination of the corresponding nFU. Therefore, if the aim of any certain food item is not to provide some of those specified nutritional properties, technically it should be excluded from the analysis, as it is not functionally comparable with other items.

In case of the comparison where all food items fulfill the nutritional requirements specified by the specific nFU, the nLCA still does not take into account any functions that are not included in the specific nFU, although such functions may exist. The provision of energy is a good example of such a function. The use of the system expansion can technically provide a solution for all these limitations; it allows the inclusion of any additional function in the assessment, even if that function may be relevant for some food items included in the comparison and totally irrelevant for some others.

Method

The GWP of different protein sources was determined by applying the LCA methodology as specified in the ISO 14040 standard[20]. The FU of the assessment was determined to be *1% of the daily requirement of a 75 kg adult for all essential and conditionally essential amino acids*, and the reference flow was the amount of a food product that would fulfill this required function. In addition to the main function (delivery of amino acids), an additional function was also considered, namely *the delivery of energy for human metabolic functions*. Instead of using allocation to distribute the climate impact between these functions, a system expansion approach was used. This is consistent with the ISO 14044[21] hierarchy of methods for handling co-products, where system expansion is preferred over any allocation method.

The following protein sources were selected for the analysis: 1) Chicken meat, 2) Beef, 3) High-fat (65%) pork, 4) Low-fat (4%) pork, 5) Milk, 6) Cheese, 7) Eggs, 8) Nuts (almonds), 9) Green peas, 10) Soybeans and 11) Quinoa. These food items were selected for demonstrative purpose only, as the aim of this study was the development of the methodology and highlighting the properties of different food items that would affect their climate impacts, rather than a comprehensive comparison of different protein sources. Most of these items were included also in the earlier comparative study by McAuliffe et al.[12], so this selection would make it possible to compare the effects of the methodological choices of the system expansion-based approach with the approach based on the nutritional index as applied by McAuliffe et al.[12].

As a starting point, the amount of each protein source was quantified that would provide a certain amount of "balanced protein", or more specifically 1% of the daily requirement of all essential and conditionally essential amino acids, i.e. the amino acids that are necessary for human metabolism but cannot be produced by human body. To fulfill this criterion, the following 11 amino acids were included in the comparison: tryptophan, threonine, isoleucine, leucine, lysine, valine, histidine, phenylalanine, tyrosine, methionine and cysteine. In practice, the required amount of the protein source was determined by the "limiting amino acid". This means that the amount of each food item was increased until the needed amount of the amino acid with the lowest concentration in comparison to the 1% of the daily requirement was reached.

After determining the required amount of food item that would provide the required amount of digested amino acids, the energy content of each food item was calculated. For most animal-based food items, energy is provided in the form of fat, in addition to the energy obtained from protein. Therefore, to allow the comparison between all food items included in the study, fat, or more specifically vegetable oil, was selected as an additional food item to be included in the assessment based on system expansion. In this analysis, the energy contained in the vegetable oil was replaced by energy contained in the compared protein sources in form of carbohydrates, fat and protein, and the amount of substituted vegetable oil was included in the analysis as negative consumption.

The general principle of the system expansion framework is presented in Fig. 2. The figure shows the comparison of two hypothetical protein sources, one with low energy content (Protein source 1) and one with high energy content (Protein source 2). The energy content of Protein source 1 is set as a baseline, and the amount of vegetable oil corresponding the additional energy content of Protein source 2 is substituted and included in the comparison as negative emissions.

It appeared that of the compared items, chicken meat had the lowest energy content, and that was used as a baseline where no vegetable oil was substituted. As a result, eleven combinations of food items (protein source + substituted fat) were formulated, each fulfilling the required amount (i.e. 1% of the daily requirement) of essential and conditionally essential amino acids, and also including the additional provision of energy as negative consumption of vegetable oil. So, these combinations were considered to be functionally equal, and therefore comparable in LCA.

The nutrient concentration, including all the essential and conditionally essential amino acids and total energy of the selected food items, was obtained from the USDA[28] database (Table 1). The amino acid digestibility of most of the protein sources was obtained from Adhikari et al.[29], similarly as in the study by McAuliffe et al.[12]. For those protein sources that were not included in the Adhikari et al. study (chicken meat, almonds, quinoa), data from Faber et al.[30], House et al.[31] and Ruales and Nair[32] were used.

An LCA approach following the ISO 14040 standards was applied[20]. As an output of the assessment, the GWP based on the IPCC 2013 impact methodology with a 100-year timescale was determined for each combination of protein source and vegetable oil. The mass-based greenhouse gas (GHG) intensity of the food items (i.e. GHG emissions per 1 kg of food item) was obtained from recent scientific literature, concentrating, for consistency, on food production in Finland. The emissions of beef and milk were calculated by Hietala et al.[33], the emission of peas by Hietala et al.[26], emissions of pork by Hietala et al.[27], emissions of broiler meat by Usva et al.[34] and emissions of eggs by Silvenius[35]. For the soybeans, the emissions of Brazilian soybean production were obtained from the ecoinvent 3.6[36] database and were used consistently with the calculation of the emissions of the meat products included in the study. The GWP of quinoa was obtained from Lotfalian Dehkordi and Forootan[37]. The GWP of the remaining food items almonds, cheese and vegetable oil (rapeseed oil) was also obtained from the ecoinvent[36] database.

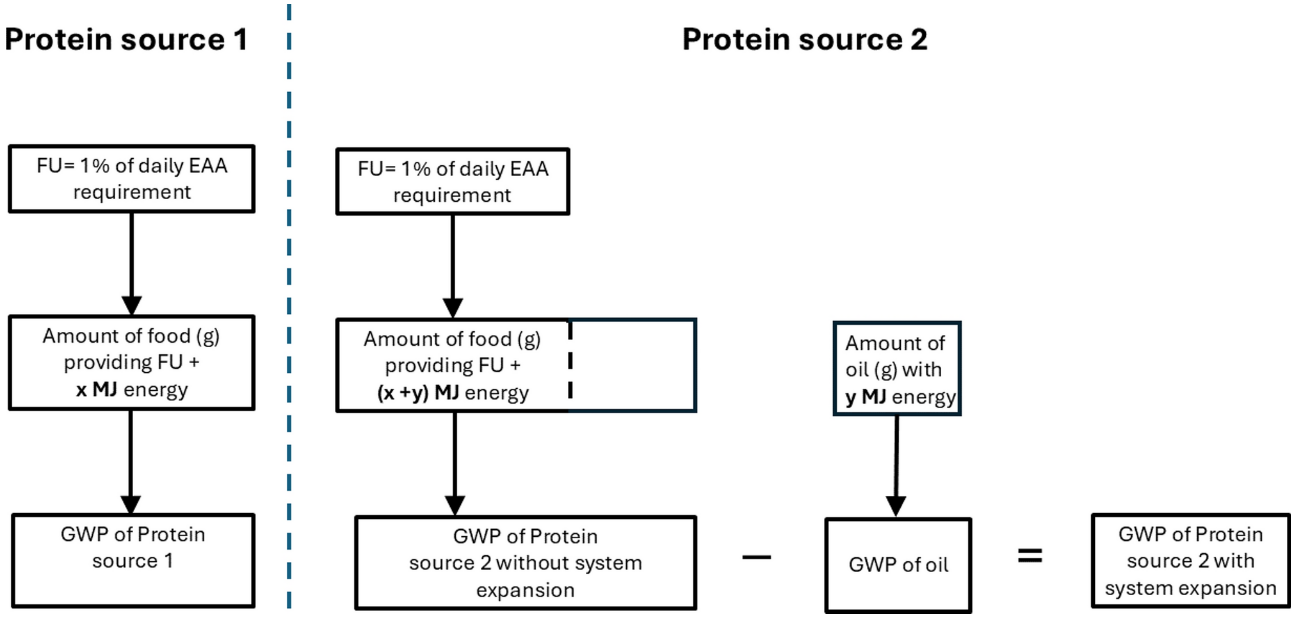

Fig. 2. The principle of the system expansion-based LCA framework for the essential amino acid (EAA) and energy content of protein sources when comparing their Global Warming Potentials (GWP). The figure shows the comparison of two hypothetical protein sources, one with low energy content (Protein source 1) and one with high energy content (Protein source 2). The energy content of Protein source 1 is set as a baseline, and the amount of vegetable oil corresponding the additional energy content of Protein source 2 is substituted and included in the comparison as negative emissions.

Content in 100 g of product	Chicken	Cheese	Beef	Egg	High-fat pork	Low-fat pork	Milk	Nuts	Peas	Soybeans	Quinoa	Daily requirement
Energy, kJ	501	1490	1160	599	2640	507	268	2420	339	614	1540	
Tryptophan, g	0.283	0.352	0.168	0.167	0.11	0.272	0.046	0.211	0.037	0.157	0.167	0.300
Threonine, g	1.01	**0.93**	0.474	0.556	0.407	0.895	0.148	0.601	0.203	0.516	0.421	1.125
Isoleucine, g	1.1	1.31	**0.584**	0.671	0.438	0.964	0.198	0.751	0.195	0.57	0.504	1.500
Leucine, g	**1.86**	2.56	1.2	**1.09**	0.761	1.68	0.321	1.47	0.323	0.926	0.840	2.925
Lysine, g	2.16	2.65	1.16	0.912	0.823	1.82	0.26	0.568	0.317	0.775	0.766	2.250
Valine, g	1.16	1.81	0.915	0.858	**0.468**	**1.06**	0.22	0.855	0.235	0.576	**0.594**	1.950
Histidine, g	0.839	1.03	0.443	0.309	0.376	0.834	0.089	0.539	0.107	0.348	0.407	0.750
Phenylalanine, g	0.908	1.43	0.644	0.68	0.384	0.898	0.158	1.13	0.2	0.586	0.593	-
Tyrosine, g	0.81	1.45	0.381	0.499	0.366	0.893	0.158	0.45	0.114	0.464	0.267	-
Phenylalanine + Tyrosine, g	1.718	2.88	1.025	1.179	0.75	1.791	0.316	1.58	0.314	1.05	0.860	1.875
Methionine, g	0.585	0.719	0.426	0.38	0.254	0.564	**0.082**	**0.157**	0.082	**0.157**	0.309	0.750
Cysteine, g	0.236	0.254	0.23	0.272	0.104	0.244	0.03	0.215	0.032	0.118	0.203	0.300
Methionine + Cysteine, g	0.821	0.973	0.656	0.652	0.358	0.808	0.112	0.372	**0.114**	0.275	0.512	1.125

Table 1. The content of energy and essential and conditionally essential amino acids of the protein sources per 100 g of product, and the daily requirement of a 75 kg human for those amino acids. The limiting amino acid of each protein source is indicated by bold font.

Data availability

All the data used in the analyses are publicly available and the sources of the data are indicated in the References section. For further needs, please contact the corresponding author.

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I.L. developed the concept and wrote the main manuscript text. P.K. carried out the data analysis. S.H., K.U. and M.S. contributed to writing.

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Additional information

Correspondence and requests for materials should be addressed to I.L.

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