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Development and application of a nutritional quality model for life cycle assessment of protein-rich foods

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ABSTRACT

Alternative protein sources (APSs) have emerged as a potentially healthy and, presumably, environmentally sustainable solution for meeting future food demand. Here we develop a new complex nutrient profile model to assess the nutritional quality of protein-rich foods, which, concurrently, allows to evaluate their environmental implications efficiently through the application of life cycle assessment (LCA). The development of the index was guided by the identification of priority nutrients in APSs and main deficiencies of similar models, which gave rise to the 'quality Nutrient Rich Food 1.10.2' (qNRF1.10.2). This model is the first nutrient profile system that combines various essential nutrients and a protein quality scoring system, namely Digestible Indispensable Amino Acid Score (DIAAS). From a nutritional perspective, its accuracy was proven and its application identified animal products as the most nutritionally complete food group, surpassing plant-based alternatives. However, when using the index as functional unit in LCA of protein-rich foods, we discovered that seeds, nuts, and mixtures of vegetable foods reported the lowest environmental impacts as a function of their nutrient density. Some exceptions were found for algae or insects, which performed worse than animal-derived foods in terms of resources consumption, or for cereals, which shown an important water deprivation potential. These results suggest that we should find a trade-off between the production of emerging and conventional foodstuffs, and that main environmental issues of each region should condition the location of production systems.

1. Introduction

Based on population growth trends and projections, how to eradicate global hunger – one of the Sustainable Development Goals – and feed the future world have become major global societal challenges (van Dijk et al., 2021). In particular, forecast for protein consumption is of special concern: demand for animal-derived protein will double by 2050, driven by socio-economic changes, increased urbanization and aging population (Henchion et al., 2017). Without changes in current standard dietary patterns, this would entail troubling environmental consequences linked to unsustainable land, water and energy use, increase of nitrous oxide and ammonia emissions to the air, nitrogen and phosphorus water pollution, and a shocking negative impact on biodiversity (Detzel et al., 2022). To break free from this cycle, alternative protein sources (APSs), which compress more conventional plant-based products and emerging foodstuffs like algae, insects or culture meat, exhibit great potential to meet dietary demands in a health-conscious and consumer-recognized sustainable manner (Kaur et al., 2022).

To support this assertion, life cycle assessment (LCA) has been widely employed by numerous authors, who have consistently reported superior environmental performance for plant-based (Kustar and Patino-Echeverri., 2021), insect or mycoprotein products (Smetana et al., 2021), as compared to animal-derived counterparts like chicken (Cheng et al., 2023) or beef (Hietala et al., 2021). However, in an important part of studies a mass-based functional unit (FU) is applied, which actually does not reflect the function of the product system. This leads to unrealistic comparisons as environmental outcomes are strongly affected by the nutritional contribution (O et al., 2023). Others address a minimalist nutritional LCA approach by considering the energy content or the quantity of protein (Shanmugam et al., 2023). In this regard, two main limitations stand out. On the one hand, although a protein-based FU may seem logical, it is insufficient to represent the actual bioavailability of amino acids, which is the assumed purpose of protein intake (Berardy

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Nomenclature

Acronyms

ADP	abiotic depletion potential
AP	acidification potential
APS	alternative protein source
DIAAS	digestible indispensable amino acid score
DRI_i	daily recommended intake for nutrient i
DRI_p	daily recommended intake for protein
ED	energy density expressed in kcal/100 g product
EF_{i100g}	environmental impact on category i caused by a specific product and measured per 100 g of product
$EF_{iqNRF1.10.2}$	environmental impact on category i caused by a specific product and expressed per qNRF1.10.2 score
$EF_{overall}$	weighted environmental impact of each food product
EP	eutrophication potential
FU	functional unit
GWP	global warming potential
IAA	indispensable amino acid
IR	ionizing radiation
LCA	life cycle assessment
LIM	limiting nutrient score
LU	land use
MRI_j	maximum recommended intake for nutrient j
$nEF_{iqNRF1.10.2}$	normalized environmental impact on category i caused by a specific product and expressed per qNRF1.10.2.
N_i	normalization factor
NR	nutrient rich score
$Nutrient_i$	amount of nutrient i (positive) in 100 g of food
PDCAAS	protein digestibility-corrected amino acid score
PM	particulate matter
POCP	photochemical ozone creation potential
Protein (in Eq.)	protein content in 100 g of food
PUFA	polyunsaturated fatty acid
qNR	quality nutrient rich score
qNRF1.10.2	quality nutrient rich food 1.10.2 score
W_i	weighting factor
WU	water use

Symbols

Ca	calcium
Fe	iron
Mg	magnesium
Na	sodium
Zn	zinc

et al., 2019). For that reason, attention should be paid to the dietary protein quality, which is characterized by the indispensable amino acid (IAA) content and digestibility (Herreman et al., 2020), and which has already been identified as a necessity in (protein-rich) food LCAs (McAuliffe et al., 2023). On the other side, general statements about the suitability of alternative products based on the protein may be too simplistic, as the effects depend on the dietary matrix and accompanying nutrients (Kurek et al., 2022). In this respect, a scarce number of investigations consider nutrient density models to include minerals, vitamins and other bioactive compounds that a consumer expects to receive from protein-rich foods (Saget et al., 2021).

In light of these methodological gaps and to the best of our knowledge, there is no indicator or scoring system that addresses all the necessary aspects. Therefore, how can we evaluate the nutritional profile of protein-rich foodstuffs and their environmental performance in a comprehensive manner that best reflect their properties? This is the final question that this article seeks to resolve, and to this end two main objectives are proposed: (i) to develop a new complex nutrition-based model that meets the needs outlined above, and (ii) to apply the model in the LCA of protein-rich foods. This latter evaluation will allow testing the model and conducting direct comparisons of emerging APSs and their animal-based counterparts. The novelty of the article is justified by the development of the novel approach, resulting in the first nutrient profiling model that combines both quantity and quality of nutrients. In addition, the research outcomes will be of interest to a wide audience, including but not limited to nutritionists, LCA-practitioners, food supply stakeholders, consumers or policy-makers.

2. Literature review

The need to compare foods from a nutritional perspective in an effective and simple way for consumers has led many authors to develop different profile models or indicators, especially in recent years when concern for health and nutrition has increased and important changes in dietary patterns are taking place. One of the best-known examples that helps consumers evaluate the healthiness of a product and enables informed and conscious food choices is the Nutri-Score (Hagmann and Siegrist, 2020), This model values the food category (nuts, fruits, vegetables, etc.) as well as the quantity of fiber and protein as positive nutrients, and energy, saturated fat, salt and sugar as negatives. Another well-recognized family of nutrient profiling models is the Nutrient Rich scores (Drewnowski, 2009), which use an across-the-board criterion, i.e., it is used to evaluate foods of different categories. There is a wide range of variants of this model, which adjust the selection of nutrients according to the expected application. Generally, the choice of nutrients is based on regulatory frameworks and dietary guidance of the region, as well as on the prevalence of specific vitamins or minerals and the adverse health effects caused by the inadequate intake of certain nutrients (Fernández-Ríos et al., 2021). Some variants also focus on adapting the indicator for the elderly, including more concerning nutrients to this segment of the population, such as selenium or cholesterol (Berendsen et al., 2019). On the other hand, authors have developed systems for the evaluation of specific food categories, for instance, seafood (Hallström et al., 2019; Entrena-Barbero et al., 2023). In these cases, valuable compounds contained in fish are introduced, e.g., omega-3 fatty acids or selenium. Similarly, Kyttä et al. (2023) proposed a product-specific index for protein-rich foods. In this study, three variants were designed according to their objective: a baseline index with the nutrients typically contained in protein-rich sources, a scarce nutrient index, which includes nutrients that are deficient among the Finnish population, and a dietary shift index that considers nutrients that should be reduced with dietary change. However, there is a gap in the existing models that has been identified by numerous authors (McAuliffe et al., 2023; Green et al., 2021; Sonesson et al., 2017). Evidence demonstrates the importance of considering protein quality when designing dietary recommendations, especially when it comes to meat consumption. Nevertheless, this aspect is often overlooked or oversimplified (Pikosky et al., 2022). The incorporation of a protein quality metric would provide greater insights, not only from a nutritional perspective, but also from an environmental framework. Besides provide a greater stratification between foods (Green et al., 2021), it may help find the balance between better digestibility of animal proteins but greater environmental impacts. In fact, Sonesson et al. (2017) conducted an LCA to different food items applying as FU different protein quality metrics, which evidenced that the level of detail of the FU has a significant influence on the results. In addition, it highlighted the need for a more complex approach that introduces a set of additional nutrients besides protein, as suggested by McAuliffe et al. (2023), which constitutes a pending task and leaves the door open to conduct this research.

3. Methods

3.1. Design of a complex nutrition quality model

The design of the nutritional model was based on the sNRF9.2 (Spanish Nutrient Rich Food 9.2) nutrient profile model, developed by Fernández-Ríos et al. (manuscript under review). A description of this index is provided in SI. As this model was developed to tackle the nutritional shortfalls of the Spanish population, we considered it appropriate as a proxy at the European level, location taken as reference for application of the model. Given that Spain shares dietary patterns, e.g., the Mediterranean Diet, with several European countries, such as Italy, France, Greece, Portugal, etc., the nutritional performance of its population may reflect that of a wider range of regions. Moreover, the general characteristics of the sNRF9.2 were considered optimal: it is based on the definition of scores and thresholds, and takes an 'across-the-board' criterion by including nutrients that should be encouraged (positive) and nutrients to limit (negative).

However, some modifications were made to achieve a more specific model for this goal. Weighting factors were not applied since the objective is not to meet specific nutritional deficiencies but to nourish in a more complete way through APSs. Protein and vitamin B12 were included as nutrients to encourage as they are the key nutrients provided by animal-based products and must be considered when evaluating potential substitutes. They totaled 11 positive nutrients: fiber, protein, vitamins A, B9 (folate), B12, D and E, zinc (Zn), magnesium (Mg), calcium (Ca) and iron (Fe). On the other hand, negative nutrients remained the same: sodium (Na) and polyunsaturated fatty acids (PUFAs) were included whereas added sugar was omitted since it is not of interest in this type of foodstuffs. Another important characteristic of the model is the inclusion of a protein quality scoring system. The Digestible Indispensable Amino Acid Score (DIAAS) was chosen as recommended by the Food and Agriculture Organization (FAO), in replacement of the PDCAAS (Protein Digestibility-Corrected Amino Acid Score). In this protein quality measure, dietary IAAs are treated as individual nutrients, whose bioavailability is evaluated based on the true ileal digestibility (FAO, 2011). Eq. (1) shows the DIAAS calculation procedure.

$$\text{DIAAS }(\%) = 100\cdot lw\left[\frac{\text{mg of digestible dietary IAA in 1g of dietary protein}}{\text{mg of the same dietary IAA in 1g of the reference protein}}\right] \tag{1}$$

where *lw* means the lowest value of the ratio. The digestible IAA content (dividend) is calculated by the mg of IAA in 1 g of protein of food multiplied by the true ileal digestibility coefficient for the same dietary IAA, and the IAA content of the reference protein (divisor) is obtained from the recommended IAA scoring pattern (Wolfe et al., 2016). For protein mixtures, the DIAAS should be calculated from the weighted average digestible amino acid content (FAO, 2011). Steps for the calculation of DIAAS are reported in Supplementary Information (SI).

Integrating all the components mentioned above, the qNRF1.10.2 (quality Nutrient Rich Food 1.10.2) was born. The algorithms for the estimation of the qNRF1.10.2 scores referred to 100 kcal of product are exposed in Eq. (2), Eq. (3), Eq. (4) and Eq. (5).

$$qNRF1.10.2 = qNR1 + NR10 + LIM2 \tag{2}$$

$$qNR1 = \frac{protein\cdot DIAAS}{DRI_p}\Big/ED \tag{3}$$

$$NR10 = \sum_{i=10}\left(\frac{nutrient_i}{DRI_i}\right)\Big/ED \tag{4}$$

$$LIM2 = \sum_{j=2}\left(\frac{L_j}{MRI_j}\right)\Big/ED \tag{5}$$

where *protein* is the protein content in 100 g of food, *DIAAS* the DIAA score (%) obtained for the food, DRI_p the daily recommended intake for protein, $nutrient_i$ the amount of nutrient *i* (positive) in 100 g of food, DRI_i the daily recommended intake for nutrient *i*, L_j the amount of nutrient *j* (negative) in 100 g of food, MRI_j the maximum recommended intake for nutrient *j* and ED the energy density expressed in kcal/100 g of product. In case that the scores were estimated with a calculation base of 100 g, the *ED* term would be ignored. All the steps for the estimation of qNRF1.10.2 scores are explained in Table A.3 of SI.

3.2. Application of the qNRF1.10.2 model in protein-rich foods

First of all, the validation of the model was conducted by using content and construct evaluation methods. The former proves the consistency of the model by comparing its nutrients with those that reflect a quality diet, whereas the latter assesses the classification of foods determined by the new system versus those established by a reference model (Poon et al., 2018). The Nutrient Rich Food 9.3 (NRF9.3) index was chosen as reference since it has been subjected to validation by convergence and showed a strong relation with global measures of diet quality (Fulgoni et al., 2009). Additionally, a comparison with the sNRF9.2, the root indicator of qNRF1.10.2, and the product-group-specific for protein-rich sources developed by Kyttä et al. (2023) were conducted to monitor trends in results.

The testing of the model was performed by applying it to different food sources. To do so, the selection of foods to be evaluated was firstly carried out. This step was mainly subjected to data availability on DIAAS or, instead, the true ileal digestibility values to calculate the protein quality index. On the one hand, different conventional animal-based products were included for assessment in order to compare them with the APSs, compressing eggs, whey, pork or beef at different cooking grades. On the other side, APSs involved a wide range of products. Some consisted of conventional protein-rich foods, such as nuts, legumes, cereals or seeds, e.g., rice, quinoa, chickpea, barley or soy, whereas others covered emerging novel products, such as algae (spirulina) or insects (yellow mealworm or banded cricket). In addition, some roots and vegetables were added to the list. Although the protein content, as well as the DIAAS, of these plant-based products are frequently low, the mixture of legumes and vegetables makes the deficiency of the most limiting IAA compensated if it is considerably present in the other food, making it a potential substitute for meat (Herreman et al., 2020).

The nutritional compositions of the products were compiled from the BEDCA (Spanish Food Composition Database) (BEDCA, 2023) and the USDA database (American Food Composition database) (USDA, 2023). DRI and MRI values were extracted from Moreira et al. (2016). When information of any specific nutrient is not available in this source, it was compiled from EFSA (2017) and European Commission (2011).

3.3. Life cycle impact assessment and integration of the designed model into LCA

Environmental impacts of animal-based products and APSs were calculated in SimaPro v9.3 using the Agribalyse v3.0.1 database (Asselin-Balençon et al., 2020). This database is built upon previous versions of Agribalyse datasets (ADEME, 2023), Ecoinvent (Moreno Ruiz et al., 2018), ACYVIA (Agence de la transition écologique, 2023) and WFLDB (Quantis, 2023). It was considered optimal to compile environmental burdens linked to food production systems due to the wide variety of products it contains as well as the high quality of the data (Colomb et al., 2015). One exception was the environmental performance of insects, which was not available in the database and, instead, was taken from Dreyer et al. (2021) and Halloran et al. (2017). In the case of vegetable mixtures, environmental impacts were estimated by weighting according to composition. The system boundaries of the processes selected were set from cradle to market, i.e., comprising from the raw materials production to the distribution to supermarket, and including processing, packaging and intermediate transportation through the product life cycle.

The outcomes were subjected to eight impact categories: GWP (global warming potential), LU (land use), water use (WU), AP (acidification), ADP (abiotic depletion) of fossil and mineral resources, and EP (eutrophication) of freshwater and marine environments. These indicators were chosen to provide a global perspective on the environmental performance of the food products, addressing emissions to different compartments – water, air and soil – as well as the consumption and use of resources, which constitute the most concerning issues of food systems. To translate the inputs and outputs of the product systems into the environmental impacts, the Environmental Footprint 3.0 method was applied. This method is the recommended by the European Commission to adopt a common way of measuring and communicating the environmental performance of products and organizations (European Commission, 2021) and it is composed of different recommended models to estimate each indicator, e.g., AWARE for water deprivation, IPCC for climate change, or CML for resource use.

For application as FU in LCA, the qNRF1.10.2 scores were estimated using a calculation basis of 100 g of product, so that the environmental impacts must be initially referred to this reference too. Therefore, the nutritionally-invested environmental impacts were calculated as indicated in Eq. (6).

$$\mathrm{EF}_{i\,\mathrm{qNRF1.10.2}} = \frac{EF_{i100\mathrm{g}}}{\mathrm{qNRF1.10.2}_{100\mathrm{g}}} \tag{6}$$

where EF_{i100g} is the impact on the impact category i caused by a specific product and measured per 100 g of product, and $qNRF1.10.2_{100g}$ is the qNRF1.10.2 score expressed per 100 g of product. This algorithm was applied to each impact category and each food to carry out an individual analysis of the proposed products. Nonetheless, to obtain an aggregated impact value to rank foods based on their joint environmental performance, normalization and weighting were employed. For this purpose, normalization and weighting factors reported in the Product Environmental Footprint Category Rules (PEFCR), which are reported in Table 1, were utilized as presented in Eq. (7) and Eq. (8).

Table 1
Normalization and weighting factors for each impact category. Values are extracted from the Product Environmental Footprint Category Rules (PEFCR, 2018).

Impact category (*i*)	Normalization factor (N_i)	Weighting factor (W_i)
GWP	$7.76{\cdot}10^3$	22.19
LU	$1.33{\cdot}10^6$	8.42
WU	$1.15{\cdot}10^4$	9.03
ADP fossil	$6.53{\cdot}10^4$	8.92
AP	55.5	6.64
ADP mineral	$5.79{\cdot}10^2$	8.08
EP freshwater	2.55	2.95
EP marine	28.3	3.12
POCP	40.6	5.1
IR	$4.22{\cdot}10^3$	5.37
PM	$6.37{\cdot}10^4$	9.54
EP terrestrial	$1.77{\cdot}10^2$	3.91
ODP	$2.34{\cdot}10^2$	6.75

$$\mathrm{nEF}_{i_{\mathrm{qNRF1.10.2}}} = \frac{\mathrm{EF}_{i\mathrm{qNRF1.10.2}}}{\mathrm{N_i}} \tag{7}$$

$$\mathrm{EF_{overall}} = \sum_{i=13} \mathrm{W_i}{\cdot}\mathrm{nEF}_{i_{\mathrm{qNRF1.10.2}}} \tag{8}$$

where nEF_i is the normalized environmental footprint on the impact category i, $EF_{iqNRF1.10.2}$ the environmental impact on the impact category i expressed per qNRF1.10.2, N_i the person normalization factor for the impact category i, $EF_{overall}$ the aggregated environmental footprint, and W_i the weighting factor for the impact category i. In this step, all impact categories compressed in the Environmental Footprint 3.0 method, excluding toxicity-related indicators, where considered to achieve the overall environmental score. That is, in addition to the above-mentioned categories, photochemical ozone creation (POCP), ionizing radiation (IR), particulate matter (PM), ozone depletion (ODP) and EP terrestrial were taken into account. Values of the environmental impacts on these categories and a brief discussion are comprised in SI.

4. Results

4.1. Model accuracy and comparison

The accuracy of the qNRF1.10.2 model was firstly tested by content validation. The developed index showed consistency between the nutrients included and those considered of major importance in the Spanish Public Health Strategy (Spanish Ministry of Health, 2022) and, focusing on a broader context, the Strategy for Europe on Nutrition, Overweight and Obesity related health issues (European Commission, 2007). In both cases, foods with low content of salt, saturated and trans fats, and sugar should be promoted, as well as plant-based sources of nutrients. On the other hand, validation by convergence was conducted. As illustrated in Fig. 1, a strong association was observed between the qNRF1.10.2 (green color line) and the NRF9.3 (yellow color line) model. For animal products, both conventional foods and insects, the greatest discordance could be seen between the two models. This may be due to the influence of the protein quality score, while for plant-based products a better agreement was obtained. A pretty similar trend was also observed for the 'Baseline Nutrient Index' scores (purple color line) (Kyttä et al., 2023). The largest discrepancies were shown for animal foods due to consideration of a wide range of B-complex vitamins, which tend to benefit meat, eggs and other derived products. On the contrary, major disagreements were reported between qNRF1.10.2 and sNRF9.2 scores (orange color line), which makes sense since the latter has the function of identifying and prioritizing foods that serve to supply the main nutritional shortfalls. Consequently, weighting factors are used to give more importance to foods with high fiber, vitamins and minerals concentration. Therefore, scores were especially high for vegetables, legumes, nuts or seeds, unlike those of the qNRF1.10.2 that weights all nutrients equally, justifying the differences in the results.

4.2. Performance of the qNRF1.10.2 in protein-rich foods

The application of the model to different animal- and plant-based products, including emerging APSs, discovered that conventional bovine and porcine meat, as well as eggs, have complete nutritional profiles, reaching $\mathrm{qNRF1.10.2}_{100\mathrm{kcal}}$ scores up to 134 (burger 80 % lean beef) (Fig. 2; green area). Results also reinforced the evidence as to why animal-derived products are so popular; in addition to having high

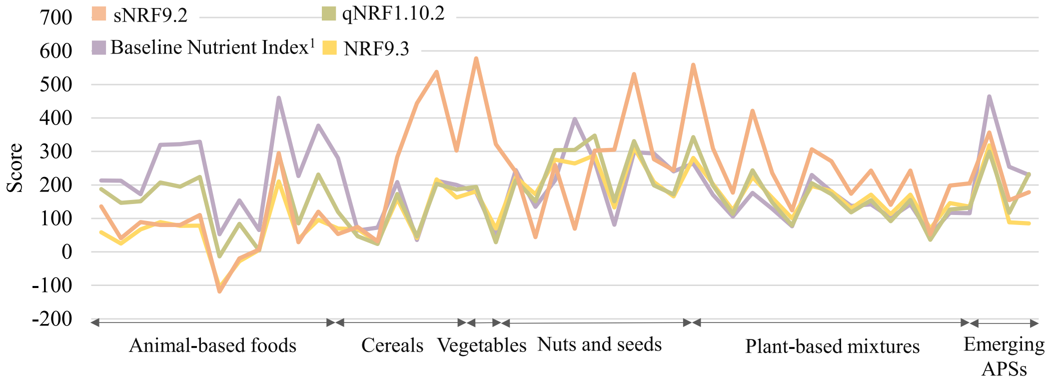


Fig. 1. Validation of the qNRF1.10.2 model and comparison with similar indicators.

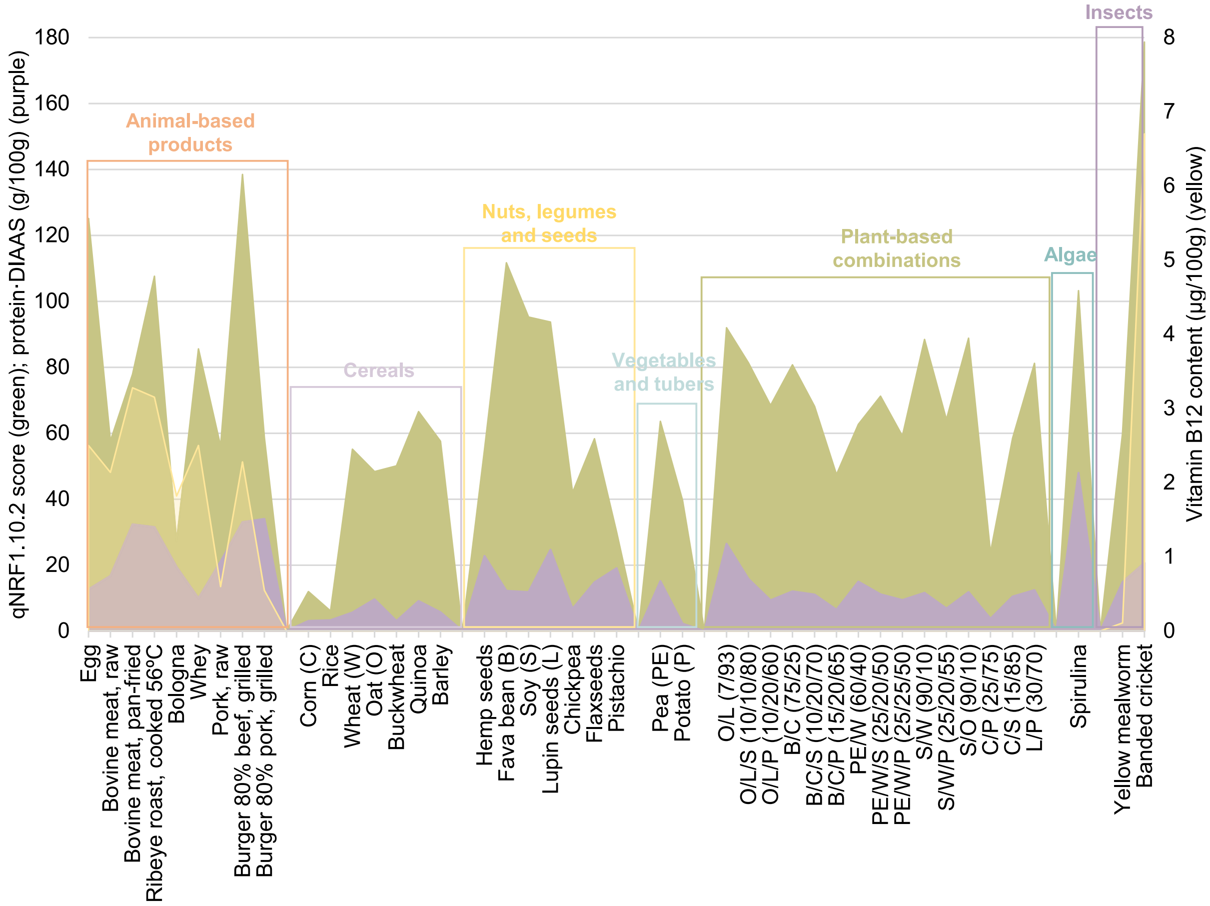


Fig. 2. Performance of the qNRF1.10.2 model. qNRF1.10.2 scores achieved for conventional animal-based products and traditional and emerging APSs. Vitamin B12 content and protein content multiplied by the DIAAS (equivalent to digestible protein content) are also represented to compare the main nutrients of protein-rich foods. O/L (7/93) or similar expressions represent a mixture of ingredients, where C: corn; O: oat; L: lupin seeds; B: fava bean; S: soy; W: wheat; P: potato; PE: pea, and the numbers indicate the proportion of each product.

protein content, the digestibility of its amino acids is the best compared to other foods, in some cases exceeding 100 %, e.g., ribeye roast (111 %) or burger 80 % lean pork (119 %) (Fig. 2; purple area). Moreover, vitamin B12 or cyanocobalamin, which plays an essential role in the health of the brain, nervous system and blood, is naturally present only in foods of animal origin, which gives them a better rating (Fig. 2; yellow area). qNRF1.10.2 scores and DIAAS can be consulted in SI.

Turning to plant-based products, cereals, vegetables and tubers reported the lowest qNRF1.10.2$_{100kcal}$ scores – below 70 – as well as a relatively low estimated bioavailable protein content this was mainly due to the insufficient digestibility of the IAAs, e.g., 47 % of rice or 36 % of corn. In contrast, nuts, legumes and seeds were awarded higher positions in the ranking, highlighting fava bean (111), lupin seeds (93) and soy (95) (Fig. 2; green area). In these vegetable products, DIAAS were estimated at between 75 and 91 %, with a maximum protein and fiber concentration of 36 g/100 g and 19 g/100 g respectively. Consequently, the combination of these food groups resulted in intermediate scores, between 23 and 91, with DIAAS reaching 100 % in some mixtures like pea/wheat/potato in a proportion of 25 %, 25 % and 50 % respectively, or fava bean/corn/potato (15/20/65).

Quite encouraging results were discovered for emerging APSs. The qNRF1.10.2$_{100kcal}$ score of dried spirulina accounted for 103, boosted by its concentration in bioavailable protein, as well as its content of other micronutrients such as vitamin E or iron. Particularly surprising was the trend of insect products. While yellow mealworm (*Tenebrio molitor*) totaled a qNRF1.10.2$_{100kcal}$ score of 60, the banded cricket (*Gryllodes sigillatus*) score was more than twofold (179), especially driven by its vitamin B12 content (Fig. 2; yellow line), which makes it the main potential alternative to meat from a nutritional perspective.

4.3. Environmental impacts based on the multifunctionality of foods

To analyze the influence of the FU selection, it was first carried out a comparison of the environmental implications of shifting from a mass-based FU – 1 kg of food – to two nutrition-related FUs – 100 g of bioavailable protein and 1000qNRF1.10.2. In order to conduct this analysis, the impact category of climate change was taken as a reference.

The analysis revealed a drastic change in the interpretation of the GWP impacts of protein-rich products when the FU of 1 kg of product moves to 100 g of digestible protein, and a more moderate influence when this in turn is adjusted to 1000qNRF1.10.2 (Fig. 3). When moving from the mass-based to the protein-related FU, the ranking of foods was almost completely modified, especially for plant products. Most meaningful changes involved alterations of more than ten positions (highlighted in Fig. 3 by means of lines). For instance, potato fell from the third position to the 25th due to its low protein concentration, and lupin seeds rise from the 19th to the fifth for the opposite reason. On the other hand, influences of moving from the simple nutrient-based FU to the complex nutrient profile model were less abrupt, although significant in some cases. For example, corn had a carbon footprint 52 % lower than flaxseeds by mass reference, whereas it was 57 % and 70 % higher per protein and qNRF1.10.2 units respectively. Likewise, spirulina rose in ranking when changing the mass reference to 100 g of protein due to its protein concentration, but dropped again when considering the overall nutritional system (from 16th to 27th) as a result of a more balanced micronutrient profile. However, there was a common negative association between GHG (greenhouse gas) emissions and conventional animal-derived products: they held the lowest positions in the ranking across all three FUs, indicating that their carbon footprints are sufficiently high to outweigh their strong nutritional profiles. A noteworthy difference emerged for eggs that remained in the middle of the list.

Another observation revolves around the variation of GHG emissions reported, tackling a considerable range of impacts from the least to the most impactful foodstuffs. Estimations of climate change were calculated 1.32 kg CO$_2$ eq./1000qNRF1.10.2 for eggs, and ranged 8.5–18.9 kg CO$_2$ eq./1000qNRF1.10.2 for meat products. It is worth mentioning the high carbon footprint of rice, which, unlike meat, was associated with the poor nutritional quality of the product rather than its environmental performance. Excluding this product, GHG emissions of cereals were below 4.1 kg CO$_2$ eq./1000qNRF1.10.2, while those of nuts, legumes, seeds, as well as plant-based mixtures were below 2.6 kg CO$_2$ eq per FU. Regarding emerging APSs, spirulina and yellow mealworm were positioned in the middle down the list, while banded cricket was at the 17th position with a GWP impact of 1.1 kg CO$_2$ eq./1000qNRF1.10.2.

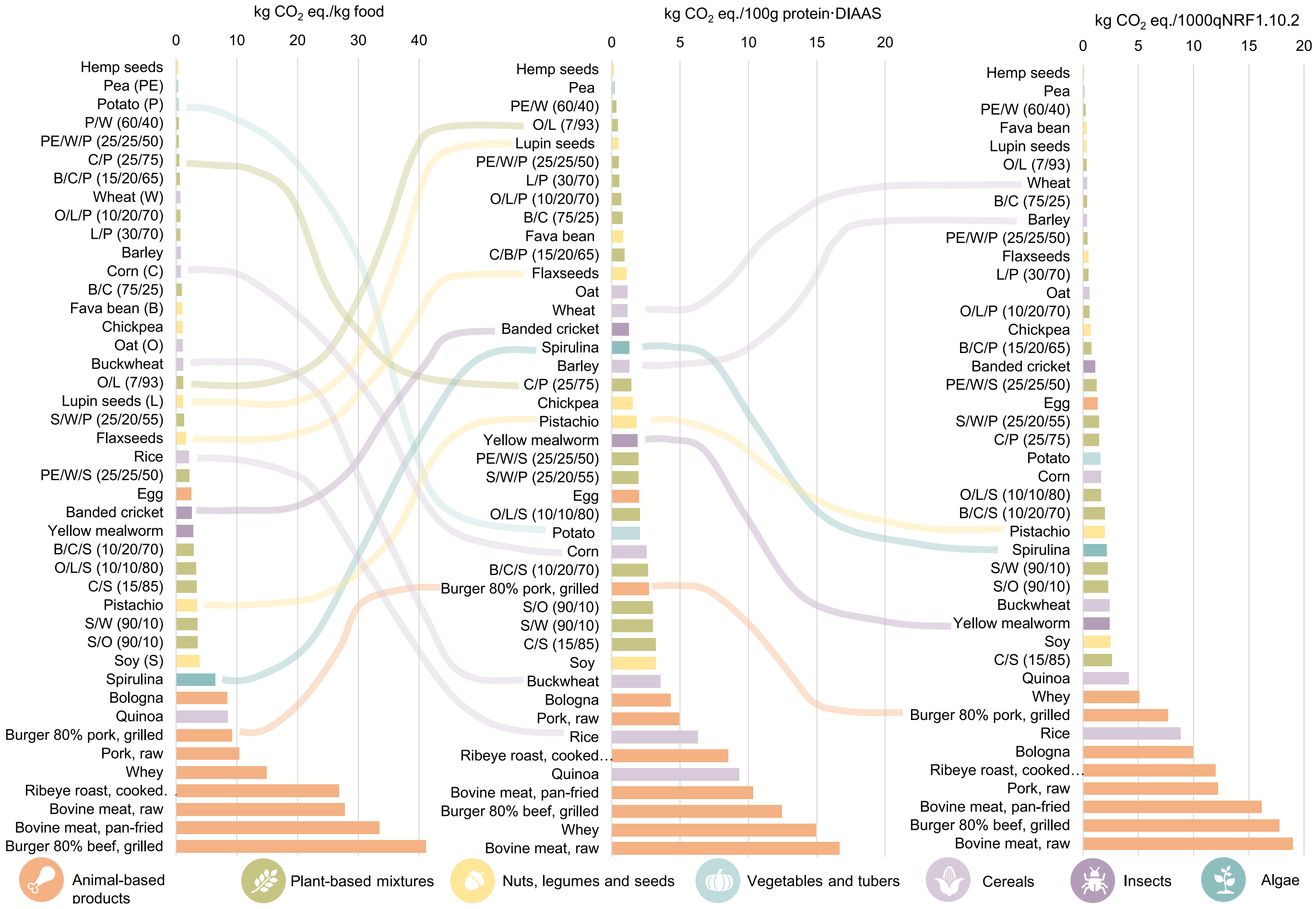


Fig. 3. Comparison of a mass-based FU and two nutrient-based FUs applied to estimate the climate change impacts of protein-rich foods. Emissions are reported per 1 kg of product, 100 g of digestible protein (protein content multiplied by the DIAAS), and 1000qNRF1.10.2. Lines linking graphs represent the most significant changes influenced by the FU selection. O/L (7/93) or similar expressions represent a mixture of ingredients, where C: corn; O: oat; L: lupin seeds; B: fava bean; S: soy; W: wheat; P: potato; PE: pea, and the numbers indicate the proportion of each product.

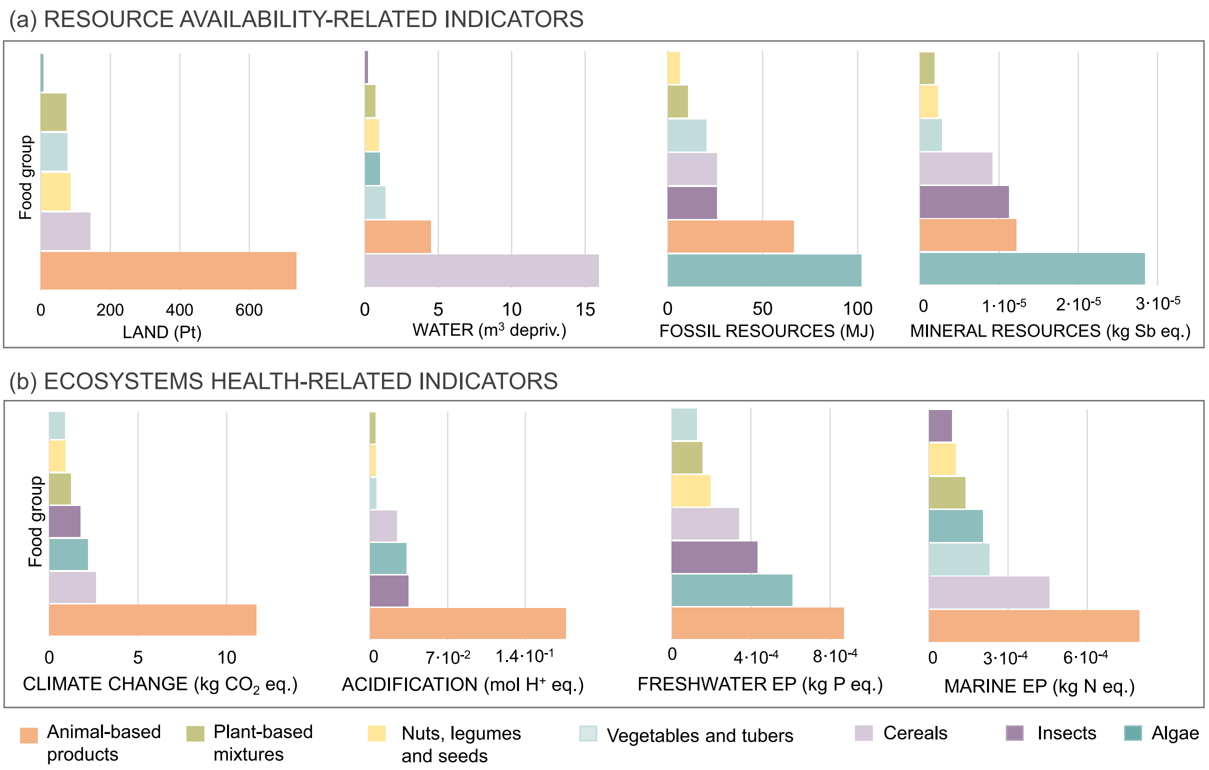
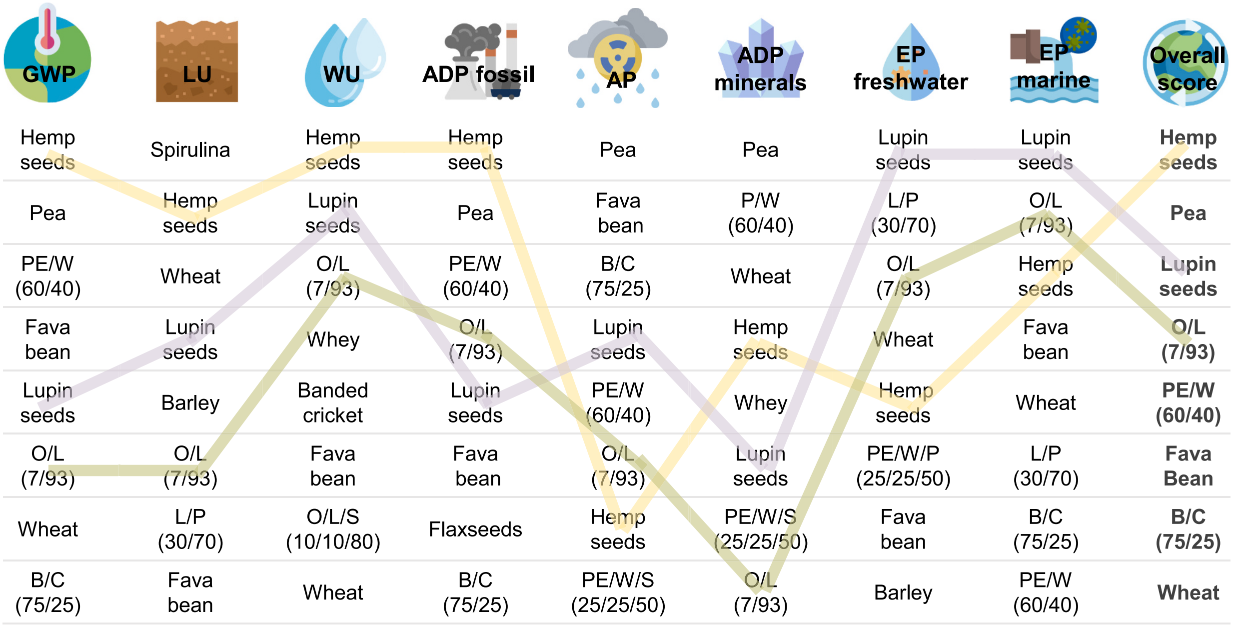


Fig. 4. Average environmental impacts associated with resource- and ecosystem- related indicators of animal-based products and APSs. The burdens reported were calculated by the average of the foods of each category using a FU of 1000qNRF1.10.2.

Impacts on other environmental indicators are shown in Fig. 4, which illustrates the rankings of the product categories based on their impacts on land and water use, acidification, eutrophication and resources depletion considering a FU of 1000qNRF1.10.2. Impacts for each independent food can be consulted in SI.

The analysis showed a series of revealing outcomes. Firstly, despite what is popularly believed, animal-based products do not always have the worst environmental performance when compared to other protein-rich foods. Although it is true that for all indicators this food group was located at the bottom of the ranking, some emerging APSs presented



GWP	LU	WU	ADP fossil	AP	ADP minerals	EP freshwater	EP marine	Overall score
Hemp seeds	Spirulina	Hemp seeds	Hemp seeds	Pea	Pea	Lupin seeds	Lupin seeds	**Hemp seeds**
Pea	Hemp seeds	Lupin seeds	Pea	Fava bean	P/W (60/40)	L/P (30/70)	O/L (7/93)	**Pea**
PE/W (60/40)	Wheat	O/L (7/93)	PE/W (60/40)	B/C (75/25)	Wheat	O/L (7/93)	Hemp seeds	**Lupin seeds**
Fava bean	Lupin seeds	Whey	O/L (7/93)	Lupin seeds	Hemp seeds	Wheat	Fava bean	**O/L (7/93)**
Lupin seeds	Barley	Banded cricket	Lupin seeds	PE/W (60/40)	Whey	Hemp seeds	Wheat	**PE/W (60/40)**
O/L (7/93)	O/L (7/93)	Fava bean	Fava bean	O/L (7/93)	Lupin seeds	PE/W/P (25/25/50)	L/P (30/70)	**Fava Bean**
Wheat	L/P (30/70)	O/L/S (10/10/80)	Flaxseeds	Hemp seeds	PE/W/S (25/25/50)	Fava bean	B/C (75/25)	**B/C (75/25)**
B/C (75/25)	Fava bean	Wheat	B/C (75/25)	PE/W/S (25/25/50)	O/L (7/93)	Barley	PE/W (60/40)	**Wheat**

Fig. 5. Top eight of APSs based on different impact categories and as an aggregated environmental footprint. The ranking was calculated with the impacts reported using a FU of 1000qNRF1.10.2. For the overall score, normalization and weighting factors were applied to all the impact categories included in the Environmental Footprint 3.0 method. O/L (7/93) or similar expressions represent a mixture of ingredients, where C: corn; O: oat; L: lupin seeds; B: fava bean; S: soy; W: wheat; P: potato; PE: pea, and the numbers indicate the proportion of each product. GWP: global warming potential; LU: land use; WU: water use; ADP: abiotic depletion potential; AP: acidification potential; EP: eutrophication potential.

higher burdens in specific indicators. For instance, spirulina was attributed with 35 % and 57 % more of the fossil and mineral resources consumption respectively than meat (on average) (Fig. 4a). This makes sense given the large amount of chemicals, nutrients and energy required for the cultivation and processing of the dried algae (Fernández-Ríos et al., 2023). There were even conventional foods that consume more water than animal products; cereals entailed a water deprivation of almost 16m^3/FU (vs. 4.8m^3). However, the bright side of emerging APSs is that, despite being critical in some specific emissions or resources, their performance is offset by their nearly neutral impact in other categories. For instance, algae exhibited a desirable role in relation to LU since it grows in water ponds, and insects had a weak influence on marine EP and water consumption as it is enough to control the humidity conditions for their growth, without the need to supply water.

Another critical remark revolves around the performance of nuts, seeds and legumes, which generally achieved positions from the first to the third, and for which the weak point resided in land occupation. Among this food group, hemp seeds, lupin seeds and fava bean highlighted as those who preside over the ranking (see SI). With less harmful environmental implications, mixtures of plant-based foods seemed to be a good alternative, ranking first in mineral ADP ($1.8\cdot10^{-6}$ kg Sb eq.) and AP ($4.6\cdot10^{-3}$ mol H+ eq.), and second in land, water and fossil resources use, as well as in freshwater EP. It is also worth noting that cereals were frequently situated at the middle of the ranking. Although foods like barley and wheat reported low environmental burdens on most of the categories, other products, especially rice, quinoa and corn, tended to penalize this group.

4.4. Aggregated environmental footprints of protein-rich products

Aggregated environmental impact values obtained through the normalization and weighting of the different impact categories are illustrated in Fig. 5. The analysis revealed that hemp seeds, lupin seeds and pea obtained scores of 18.22μPt, 29.77μPt and 25.09μPt respectively, reporting the best environmental performances. In fact, the first two foods and a mixture of oat and lupin seeds in a proportion of 7/93 not only achieved a low aggregated footprint, but also remained in the top eight of the ranking for each specific environmental indicator. On the contrary, some foods like pea or a mixture of pea/wheat (60/40) held the second and fifth positions on the overall ranking, as long as they did not appear in the top of the independent categories. This was caused by the weighting factors that give greater weight to climate change related indicators, and in which these foods showed an excellent performance. Not surprisingly, meat and other animal-derived products occupied the lowest positions at the ranking, as well as some cereals, e.g., rice, quinoa or corn, consistently with the results reported above (SI). In relation to emerging APSs, algae and insects were positioned from 23rd to 44th when ranked by aggregated impacts, suggesting that they still have some way to go to be truly competitive to more conventional alternatives.

5. Discussion

This scientific contribution synthetized empirical evidence on the environmental performance of traditional animal protein-rich products and APSs by applying the novel qNRF1.10.2 model in their LCA. The limitations of the use of single nutritional metrics for comparing the environmental implications of nutrient-dense foods posed the challenge and need to develop this interdisciplinary research. The breadth and polyvalence of the designed nutrient index enabled for more holistic and comprehensive outcomes, improving our understanding of the environmental-nutritional-health trilemma of alternative protein-rich foods. The application of the model in LCA led to the expected results: animal proteins generally have a worse environmental profile than APSs. However, this statement has its limitations. The number of conventional APSs assessed corresponding to cereals, legumes or vegetable mixtures is acceptable, while emerging APSs such as algae or insects are scarce, or even non-existent in the case of culture meat or microbial protein. This increases the uncertainty in arriving at a universal conclusion. The limited number of environmental studies of these novel foods, in which data from lab experiments or at pilot scale are mostly used (Fernández-López et al., 2024), and especially the lack of nutritional data related to their protein digestibility, reduces the number of case studies. With it, the ability to fully assert that APSs are more environmentally sustainable than animal products is threatened. At the same time, data used to conduct the environmental assessments are prone to uncertainty. Both the impacts obtained from the database – animal products, vegetables, legumes – and those extracted from literature – insects – are subjected to uncertainty associated with both the intrinsic quality of the data and the variability of the production processes. The former tends to be greater in the case of insects, since it is based on an isolated case study in which the representativeness of the data is lower than that reported in the standardized and validated database. The latter is a common variable that influences all the products and must be taken into account. Impacts can vary significantly depending on the type of system: for instance, burdens of certified organic meat and dairy production differ considerably from those of conventional systems (de Vries et al., 2015), as well as those of intensive and extensive crops production (Nemecek et al., 2011). Consequently, this issue should be addressed in more detail in further research to draw reliable conclusions.

On the other hand, the interpretation of the results and how they are presented can be confusing. The aggregated environmental footprints show a similar trend to the independent analyses. However, they are subjective and do not provide consumers, policymakers and other stakeholders with accurate and transparent data, which hinder for truly conscious decision making. Normalization and weighting procedures provide a simple and understandable way of conveying information and ensure that the focus is placed on priority issues, but it should be taken with caution and taking into consideration the different variables that may influence it. In this line, it is worth noting that the introduction of APSs in food habits and the changes in dietary patterns should be driven firstly by food security. Ensuring basic nutritional needs must be a priority, so in developing countries with limited access to food, environmental issues should take a back seat and food decisions should be subjected to food availability. On the other hand, where access to nutritious products is not a problem, attention should be directed towards production systems, which must be conditioned by major environmental concerns. For instance, water deprivation and arable land use are critical in Spain (Green et al., 2021). In this region, the consumption of seeds, legumes and nuts would be encouraged, whereas the introduction of emerging APSs, for instance spirulina, should find a trade-off between high water consumptions and low land occupation. Based on this, it is vitally important to pay attention to the specific environmental problems of each region. Accordingly, it should be promoted the development of regional indices based on nutritional shortfalls to estimate robust nutritionally-invested environmental impacts that allow the design of strategies to achieve a more sustainable sector.

6. Conclusions

This article develops a new complex nutrient profile model to assess the nutritional and environmental profile of protein-rich foods, paying special attention to animal-based products and conventional and emerging APSs. To do so, a multidimensional perspective was addressed, introducing the quantity and quality of protein and the presence of minerals, vitamins and other macronutrients into the indicator. The qNRF1.10.2 proved its applicability and relevance in the scientific field, showing a strong correlation with other well-known validated models. Besides, it performs in accordance with public health strategies, providing adequate food prioritization in line with quality dietary standards. Its application evidenced superior nutritional profiles of conventional animal-derived foods and insects due to the presence of vitamin B12 and higher protein quality, and followed by nuts, legumes and seeds and plant-based mixtures.

The use of the model as a functional unit was extended to products from different food groups, demonstrating its versatility and ability to complement environmental analyses and to report consistent results based on the actual function of the food. The influence of the results based on the FU selection was evident, with impacts varying very significantly from a mass-based to a protein-based FU, and with more moderate changes when shifting to the nutrient profile model as FU. By applying the latter, we discovered that, although their environmental profile is generally quite bad, animal products are not always the worst. Emerging APS, especially insects and algae, while performing enviably in some impact categories, have clear weaknesses probably associated with nascent production and market, as well as the lack of processes optimization. These facts hinder them to be competitive, especially with more traditional plant-based alternatives. Consequently, the identification of the critical points will allow stakeholders to focus efforts and try to improve production systems based on more efficient use of water, energy and natural resources.

CRediT authorship contribution statement

Ana Fernández-Ríos: Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Conceptualization. **Laura Batlle-Bayer:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Sahar Azarkamand:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Jara Laso:** Writing – review & editing, Conceptualization. **Pere Fullana-i-Palmer:** Writing – review & editing. **Alba Bala:** Writing – review & editing. **Rita Puig:** Writing – review & editing. **Rubén Aldaco:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **María Margallo:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.07.026.

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