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LCI METHODOLOGY AND DATABASES

Design of a nutrient profiling model for life cycle assessment of "superfoods" to address nutritional deficiencies and enhance environmental protection in Spain

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Abstract

Purpose The overriding connection between climate interactions and nutritional outcomes of food systems is at the forefront of research, especially when it comes to assessing alternative food products. Accordingly, the objective of this paper is to design a nutrient profiling (NP) model adapted to the Spanish context for use in nutritionally-factored environmental life cycle assessments (LCA) of "superfoods."

Methods The variability in nutritional needs between countries and their associated environmental impact were the key points that motivated the creation of the model and guided its development. Based on the "nutrient rich" family of models, the characterization of the NP system was guided by the definition of the specific purpose and the selection of qualifying and disqualifying nutrients according to the Spanish recommendations. The introduction of weighting factors was motivated by the capacity of "superfoods" to cover main nutritional shortfalls of the population and they were estimated with the actual and the recommended intake levels.

Results and discussion The Spanish Nutrient Rich ("super")Food 9.2 (sNRF9.2) model validation and testing across various foods successfully fulfills its purpose by aligning with the Spanish Public Health Strategy and providing an adequate prioritization of products. The application of the index to "superfoods" identified chia seeds, turmeric, kale, or moringa, among others as the most beneficial, thus demonstrating their nutritional potential. Even though the application as functional unit in the LCA of "superfoods" is ongoing, preliminary results in conventional products showed its usefulness in conveying integrated information efficiently.

Conclusions The model represents an initial step toward advancing research, adapting a contextualized NP model for future objective environmental analysis of "superfoods." It will contribute to ensuring sustainable food security and provide new insights and perspective for decision-making by consumers, stakeholders, and policy makers.

Keywords Functional unit · Nutrient profiling model · Novel food · Environmental impacts · Nutritional deficiencies · Spanish Nutrient Rich Food

1 Introduction

Food systems are a major link between human and environmental health, nurturing the former and having potential to support the latter; however, they are currently threatening both (Willett et al. 2019). Current and expected future global diets, characterized by poor quality, high caloric intake, and nutrient deficiencies, are greatly increasing the incidence of obesity and chronic noncommunicable diseases that lower global life expectancy (Moreno et al. 2021). Moreover, they force food systems to operate beyond safe physical and ecological limits (Hallström et al. 2022). Consequently, the

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transformation of food systems is the main driver of sustainability in this sector. "Future foods," such as microalgae, insects, or other specific products also known as "superfoods," may provide nutritious alternatives while meeting multiple sustainability goals (Mazac et al. 2023), serving to replace conventional foods but also to complement and enhance current diets. However, understanding the interconnectedness between the nutritional and environmental dimensions of "novel" products is tricky due to their new inclusion in conventional food systems and their incipient consumption, which hinder the progress of sustainability initiatives in the frame of climate implications and hunger eradication (Green et al. 2021).

To address this interdisciplinary work, the search for methodologies to achieve sustainable food security is on the rise. The role of life cycle assessment (LCA) has been highlighted in shaping the prospects for food system transformation, and it can be oriented and utilized in ways that clarify thinking and help advance policy-relevant knowledge in this field (Garnett 2014). However, the simplest and most generic LCA methodologies fail to capture the relationship between the different components of food systems, commonly disregarding their function of nourishing. To address this issue, nutrition and health aspects have been included in environmental assessments of food using different approaches or methods, which can complement each other, constituting what is known as nutritional LCA (nLCA) (McLaren et al. 2021). On the one hand, health metrics have been used to assess the dietary impact on a specific health outcome by including, for instance, the potential malnutrition damage, or measuring the disability adjusted life years (DALYs) of producing and consuming foods (Ridoutt 2021a). On the other hand, nutrition-based methods aim to introduce nutrition as a function, frequently bringing nutritional properties into the functional unit (FU). According to LCA-practitioners, this is the most widespread strategy for revealing direct food impacts as a form of environmental influence (Weidema and Stylianou 2020). This strategy can be addressed by the consideration of single nutrients, satiety factors, scores based on the correlation between various nutrients, e.g., the fat and protein-corrected milk index (Baldini et al. 2017), or complex nutrient indices that measure the contribution of foods to dietary recommendations (Saarinen et al. 2017). Regarding the latter, nutrient density scores or nutrient profiling (NP) models (or indices) are seen as promising approaches for characterizing the multifunctionality of foods as they reflect the best nutritional quality in relation to a healthy diet (Bianchi et al. 2020). Complex, nonspecific indices are frequently used, but even though a generic public health indicator can lead to healthier diets in all nations, differences between environmental impacts and regions are substantial (Springmann et al. 2018). Hence, regionally explicit models focused on more localized interactions of nutritional needs and planet protection are needed (Green et al. 2021), capturing current nutritional challenges based on the dietary situation in different countries (Sonesson et al. 2017). As response, some authors have developed contextualized specific models: the Nutrient Rich Food (NRF) model developed by Drewnowski (2009) is focused on the U.S population, the nutrient density score proposed by Hallström et al. (2019) is intended for application in Sweden, and the alternative NRF designed by Ridoutt (2021b) considers the needs of Australian consumers.

Within this framework, this article aims to redesign a NP model tailored for the specific Spanish context to integrate it into combined nutritional-environmental assessments of "superfoods." This will allow to identify the most nutritious product available to meet the current nutritional shortfalls of the Spanish population at the lowest environmental cost. Given that there is not an official definition of the term and to avoid controversy, the definition of "superfoods" provided by Fernández-Ríos et al. (2022) is adopted in this research. According to this, "superfoods" must comply the following characteristics: (i) be natural, non-multicomponent products, (ii) present abnormally concentrations of any specific nutrient with respect to that of products of a comparable food group, and (iii) be "exotic," meaning traditionally produced and consumed outside Europe. Based on these features, the list of "superfoods" selected after exhaustive nutritional study and provided in this review was considered for the development of this research. For further information, consult the reference by Fernández-Ríos et al. (2022). The state of the art on NP models and nLCA suggests an important number of models and strategies, but to date, none have focused on the Spanish context or on the adaptation to assess the suitability of "superfoods," which justifies the novelty of the study. This investigation not only is important to LCA practitioners but also provides a valuable resource for nutrition specialists, food supply stakeholders, and consumers, as it enables sensible and conscious choices and helps policy makers design strategies to shape the future of sustainable food.

2 Methods

The development of an NP model must be based on iterative decision-making since a selection at one stage may affect others and must be robust and consistent with the purpose for which it is designed (Scarborough et al. 2007). The characteristics and aspects reported in the framework proposed by Green et al. (2023) were used to develop the model. Figure 1 shows a summary of the most important questions throughout the process, which will be answered in 2.1. Design of the NP model.

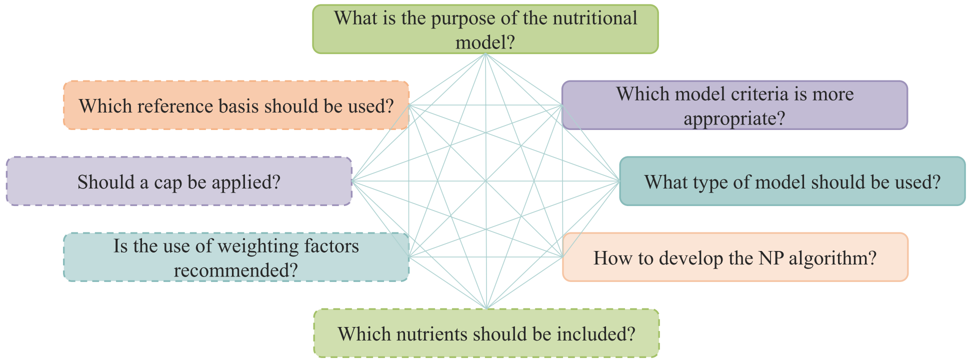

Fig. 1 Key questions to address in the development of an NP model. Solid lines represent the general characteristics of the index and dashed lines illustrate the specific features of the adapted model

2.1 Design of the NP model

2.1.1 General characteristics

The purpose of the model is to evaluate and rank the most suitable "superfoods" for tackling current nutritional shortfalls in the Spanish population. This model would provide objective guidance on dietary choices by identifying key nutritional needs and encouraging the consumption of specific products to address them.

An "across-the-board" model was considered appropriate since it uses the same criteria to categorize foods that are naturally different (Santos et al. 2021). This approach was selected instead of "group-specific" that focuses on a particular food category and its characteristics since it enables to compare all products under the same approach. In line with this, a type of model based on the definition of continuous scores and thresholds according to the nutrient content and intake recommendations would be more useful for ranking and providing a more accurate prioritization of foods. Among all the available approaches, the algorithm of the Nutrient Rich Food (NRF) family of scores, proposed by Drewnowski (2009), was used as a basis. In addition to complying with all the above-mentioned features, it is one of the most used nutrient indices (McLaren et al. 2021) and adequately represents the nutritional function of food in LCA outcomes (Fernández-Ríos et al. 2021). These models combine two subscores: NR, which is based on positive (to encourage) nutrients, and LIM, which addresses negative (to limit) nutrients. Both subscores are estimated considering the nutritional contribution of a food to the recommended daily intake (DRI) or to the maximum recommended intake (MRI).

2.1.2 Specific model approach

The NRF baseline algorithm (Eq. 1) was adapted according to specific requirements, taking the Spanish context as a reference, as well as the purpose of the index.

$$NRFn.m_{100kcal} = 100 \cdot \left(\sum_{i=1-n} \left(\frac{\text{nutrient}_i}{DRI_i} \right) / ED - \sum_{j=1-m} \left(\frac{L_j}{MRI_j} \right) / ED \right) \quad (1)$$

where nutrient_i is the content of qualifying nutrient i in 100g of food, DRI is the daily recommended intake, L_j the content of disqualifying nutrient j in 100g of food, MRI the maximum recommended intake, and ED the energy density.

In the model, contextualization for the Spanish situation was performed by considering consumption data for the Spanish population, which allows for the identification of the nutrients of interest and the estimation of the weighting factors, as well as the use of reference values for this segment. Therefore, the selection of nutrients for encouragement was guided by the deficient nutrients in Spanish diets. The data reported in the ANIBES scientific study, developed by the Spanish Nutrition Foundation, were used. The study examined energy, nutritional intake, and dietary habits, as well as socioeconomic and anthropometric influences, in Spain (FEN 2023). The data were collected from the adult population because it comprises the widest age range (18–64 years) and provides greater representativeness. First, the adequacy of the population for meeting nutritional recommendations was analyzed. The nutrients evaluated were classified into two groups according to the percentage of the population meeting 80% of the DRI. From this classification, the most deficient nutrients were chosen, i.e., those that are consumed less than 80% of the DRI in more than 50% of the population: fiber (3.95% of the population consumed 80% of the DRI), vitamin B9 or folate (4%), vitamin D (8%), Zn (9%), vitamin E (20%), Mg (22%), vitamin A (26%), Ca (26%), and Fe (37%). On the other hand, nutrients to be limited were selected for their dietetic importance due to their negative effects on health and the characteristics of the products under study. Saturated fatty acids (SFAs) and Na were considered, whereas added sugar, another detrimental nutrient usually included, was ruled out due to the nature of "superfoods," which are considered non-multicomponent products, i.e., consisting of a single foodstuff (e.g., a fruit) rather than a mixture of several products (such as a meal).

The selection of these nutrients can be considered optimal because collinearity is avoided due to nutrient correlations, which determine certain foods based mainly on a single property. This means that, for instance, a model that includes total fat, energy, cholesterol, and SFA discriminates among foods based purely on their fat content, while a score involving only minerals and vitamins may have little discrimination power (Drewnowski and Fulgoni 2009). All the steps and data for the selection of nutrients can be consulted in the Research Data file.

Other technical issues that must be addressed when creating a profiling algorithm include but are not limited to weighting and capping. The former serves to provide greater importance to specific nutrients based on an objective criterion. Although the vast majority of models do not consider weighting, the strategy for the definition of factors can be guided by multiple aspects, usually motivated by the nutritional performance of foods with the objective of favoring products that best meet the nutritional deficiencies or those that provide more energy or specific nutrients (Green et al. 2023). They can also be defined according to experts' opinion, as Mozaffarian et al. (2021) did, or employing mathematical models such as regression coefficients derived from relationships between nutrients and health, as Arsenault et al. (2012) proved in a variant of the Healthy Eating Index. In the present work, weighting was applied to highlight the need to supplement some deficiencies over others based on the Spanish consumers' needs. Ridoutt (2021b) already addressed this approach and defined weighting factors (w_i) by using the distance to target method, which enable to develop unique factors for each age and gender group in Australia and New Zealand. Similarly, Hallström et al. (2019) estimated the w_i based on the recommended intake and the real average intake in Sweden. Their outcomes demonstrate the usefulness of this method to consider the nutritional status of the studied population. Therefore, and given the expected objective of the NP model developed in this contribution, the latter strategy was adopted. w_i for positive nutrients were measured as the ratio of DRI to average intake levels of the Spanish population, while for negative nutrients, they were calculated inversely. With this methodology, nutrients most lacking in the diet have a greater influence on the final score than nutrients for which requirements are fulfilled or exceeded. Similarly, since Na and SFA are consumed above the recommended levels, a higher w_i, and consequently, penalty, is applied to the score. w_i values for each nutrient are reported in Table 1.

On the other side, to avoid crediting individuals from overconsumption of qualifying nutrients that do not lead to major health benefits (Van Kernebeek et al. 2014), their intake was capped to the DRI. This approach is particularly interesting for its application in "superfoods," since these products stand out for having extraordinarily high concentrations of certain nutrients and may tend to be overvalued if not limited. In addition, recalling the ultimate objective of the indicator, it is worth noting that negative nutrient indices acting as FUs confer a negative environmental impact, which could lead to confusion by referring to a false positive impact or avoided burdens. For this reason, although the LIM subscore is unlikely to be greater than the NR subscore, a threshold was set at 0 for the difference in these subindexes (Saarinen et al. 2017), leading to an exorbitant impact and discarding the product under study as a healthy choice. Finally, the reference unit for the score calculation was left open for convenience since when using nutritional indicators such as FU, it does not matter whether the score is based on

Table 1 Average and recommended daily intakes and weighting factors for the nutrients considered in the NP model

Nutrient	Average daily intake	DRI/MRI	Weighting factor (w_i)	Reference average daily intake
Nutrients to encourage				
Fiber (g/day)	12.59	25	1.99	González-Rodríguez et al. (2017)
Vitamin B9 (μg/day)	160.3	400	2.50	Partearroyo et al. (2017)
Vitamin D (μg/day)	4.5	15	3.33	FEN (2017)
Zn (mg/day)	8.2	15	1.83	Olza et al. (2017)
Vitamin E (mg TE/day)	7.1	12	1.69	Olza et al. (2017)
Mg (mg/day)	223	340	1.52	FEN (2017)
Vitamin A (μg RE/day)	672	1000	1.49	Olza et al. (2017)
Ca (mg/day)	689	1000	1.45	FEN (2017)
Fe (mg/day)	10.4	14	1.35	Samaniego-Vaesken et al. (2017)
Nutrients to limit				
SFA (g/day)	2026	2000	1.01	Partearroyo et al. (2019)
Na (mg/day)	33.3	20	1.2	Ruiz et al. (2016)

All DRI values were extracted from Moreira et al. (2016), except for those of fiber and Na (EFSA 2017) and from SFA (European Commission 2011) due to a lack of data availability. *TE*, α-tocopherol; *RE*, retinol; *SFA*, saturated fatty acid; *DRI*, daily recommended intake; *MRI*, maximum recommended intake mass or energy because emissions and nutritional content are calculated for the same amount of product (Saarinen et al. 2017). For that reason, and to evaluate the influence of considering the energy density of products, both bases were analyzed from a purely nutritional perspective. A reference of serving sizes was discarded as they constitute subjective metrics and they are not officially established in the EU.

2.2 Validation, sensitivity, and testing of the model

Validation of an NP model against objective measures of health is necessary prior to testing the accuracy of the model, i.e., to measure its ability to accomplish the purpose for which it was designed (Cooper et al. 2016). Content validity, which assesses whether the model classifies foods according to dietary recommendations (Poon et al. 2018), was assessed. To do so, the consistency between the food components included in the model and those highlighted in the Spanish Public Health Strategy 2022 (Spanish Ministry of Health 2022) was analyzed. In addition, validation by convergence was conducted by comparing the trends of the scores obtained for the present model and those obtained for the Nutrient Rich Food 9.3 (NRF9.3), developed by Drewnowski (2009). On the other hand, given the applicability of the developed nutritional model and the subjectivity of the aspects that create this specific indicator, a sensitivity analysis was performed by modifying two design features. Firstly, weighting factors were omitted from the model in order to analyze trends in the scores as consequence of the contextualization. Secondly, the performance of the model without truncating the metrics at 100% of the DRI or MRI was assessed by avoiding capping. For both analyses (validation and sensitivity), a selection of the most widely consumed conventional and natural foods in Spain was made in order to compare with other references. This decision was based on the versatility of the model which, although designed for "superfoods," is valid for application in any type of natural food due to its characteristics. This allows for a broader range of food groups to be included, facilitating comparison with other models and alignment with health recommendations. However, although only analyses on conventional foods are shown in the manuscript, all variants were tested on "superfoods" and the results can be found in the Research Data file. The nutritional properties of these products were compiled from the Spanish Food Composition Database (BEDCA 2024), and the database from the US Department of Agriculture (USDA 2024) for missing data. To contextualize the index, DRI and MRI data were extracted from Moreira et al. (2016), established for the Spanish population. When this information was not available at the national level, European values reported by EFSA (2017) and the European Commission (2011) were used. All the nutritional data and steps for the scores' calculation can be consulted in the Research Data file.

Finally, the model was tested in different "superfoods." The selection of these products was subjected to data availability of their nutritional properties and was based on the list provided by Fernández-Ríos et al. (2022). Consequently, nutrient content was extracted from this source (see Research Data). For this analysis, both a reference of 100 g and 100 kcal were used to analyze the influence of the energy density in the performance of the indicator.

2.3 Application of the model in LCA

A simple preliminary analysis was carried out to assess the influence of the use of this nutritional FU in LCA. For its integration, sNRF9.2 scores were estimated under a basis of 100g of product, so that the environmental impacts must be initially referred to this reference too. Subsequently, nutritionally-factored environmental burdens were calculated by the division of the environmental footprint and the nutritional quality. As a first approximation, the model was applied as FU in LCA studies of foods produced in Spain, so the selection of products was limited by this restriction. Impacts for each food product were compiled from literature and are reported in the Research Data file. Some "superfoods" with available environmental data were also incorporated. For the assessment, the global warming potential (GWP) over 100 years (considering biogenic emissions) was chosen to illustrate the environmental footprint of the foods. Given that the carbon footprint is the most commonly metric estimated in all articles and it is the only that is calculated under the same framework regardless the impact method, it was considered an appropriate selection. However, the main limitations of this decision are discussed in Sect. 4. Limitations and discussion.

3 Results

3.1 Model proposal and accuracy

The proposed model algorithm, called Spanish Nutrient Rich ("super")Food 9.2 (sNRF9.2), which has a reference unit of 100 kcal, is presented in Eqs. 2, 3, 4, 5, and 6.

$$sNRF9.2_{100kcal} = sNR9_{100kcal} - sLIM2_{100kcal} \tag{2}$$

$$sNR9_{100kcal} = 100 \cdot \sum_{i=1-9} \left(w_i \cdot \frac{\text{nutrient}_i}{DRI_i} \right) / ED \tag{3}$$

$$sLIM2_{100kcal} = 100 \cdot \sum_{j=1-2} \left(w_j \cdot \frac{L_j}{MRI_j} \right) / ED \tag{4}$$

$$w_i = \frac{DRI_i}{average\ daily\ intake} \tag{5}$$

$$w_j = \frac{average\ daily\ intake}{MRI_j} \tag{6}$$

where w_i and w_j represent the weighting factors for the nutrients to encourage (i) and limit (j), respectively; $nutrient_i$ is the amount of nutrient i in 100 g of food; DRI_i is the daily recommended intake for nutrient i; L_j is the amount of nutrient j in 100 g of food; MRI_j is the maximum recommended intake for nutrient j; and ED is the energy density (kcal) in 100 g of food. It should be noted that for the estimation of the sNRF9.2 score for a calculation basis of 100 g, instead of 100 kcal, the same algorithm was used, omitting the ED term.

Regarding the validation of the model, the Spanish Public Health Strategy identifies the high consumption of ultra-processed foods as the main reason for unhealthy eating due to their high energy value, salt, sugars, low quality fats, and low concentration of fiber and essential micronutrients. Although processed foods were not included in validation because they are outside the domain of the model, the sNRF9.2 included most of the nutrients of concern identified in the strategy, except for sugars. Figure 2 illustrates the application of the model to different natural foods, for which higher scores are associated with higher nutritional quality. The trends obtained showed its adequacy and consistency with health recommendations, with meat having the lowest scores mainly due to their high content of sodium and unsaturated fats. However, the prioritization of products changed substantially depending on the reference unit used. Using 100 kcal as a basis for calculation, vegetables, fish, fruits, and roots and tubers were placed at the top of the ranking as the most suitable foods to meet current nutritional needs. This trend is quite similar to that reported by Drewnowski (2009), who applied the NRF9.3 index developed for the American population, which indeed supports validation by convergence. In contrast, a calculation basis of 100g provided cereals and grains, and nuts, seeds, and legumes with the highest scores, followed by seafood. The explanation for this change is that sNRF9.2$_{100kcal}$ tends to penalize foods with high energy value, so fruits and vegetables are considered the most complete and balanced products providing the least energy intake. On the other hand, sNRF9.2$_{100g}$ does not discriminate by energy, so nuts, pulses, and cereals, which are the most energy-dense foods, are the main sources of the most critical macronutrients, i.e., fiber, and essential micronutrients, such as folates, magnesium or calcium. It is worth noting that fish scores were quite high for the two variants of the index, which is largely due to its vitamin D content, which is the most deficient nutrient among the Spanish population. In light of these tendencies, the model was able to establish a strong relationship between foods and the recommendations for health promotion and disease prevention, placing meat at the bottom of the ranking and setting the base products of the Mediterranean diet at the top, i.e., fruits, vegetables, cereals, and legumes.

On the other hand, Fig. 3 shows the score of foods calculated using two variants of sNRF9.2$_{100g}$: (i) sNRF9.2$_{100g}$ without weighting factors and (ii) sNRF9.2$_{100g}$ without capping. The trend in the scores observed for the three variants of the NP model is quite similar, positioning nuts, legumes,

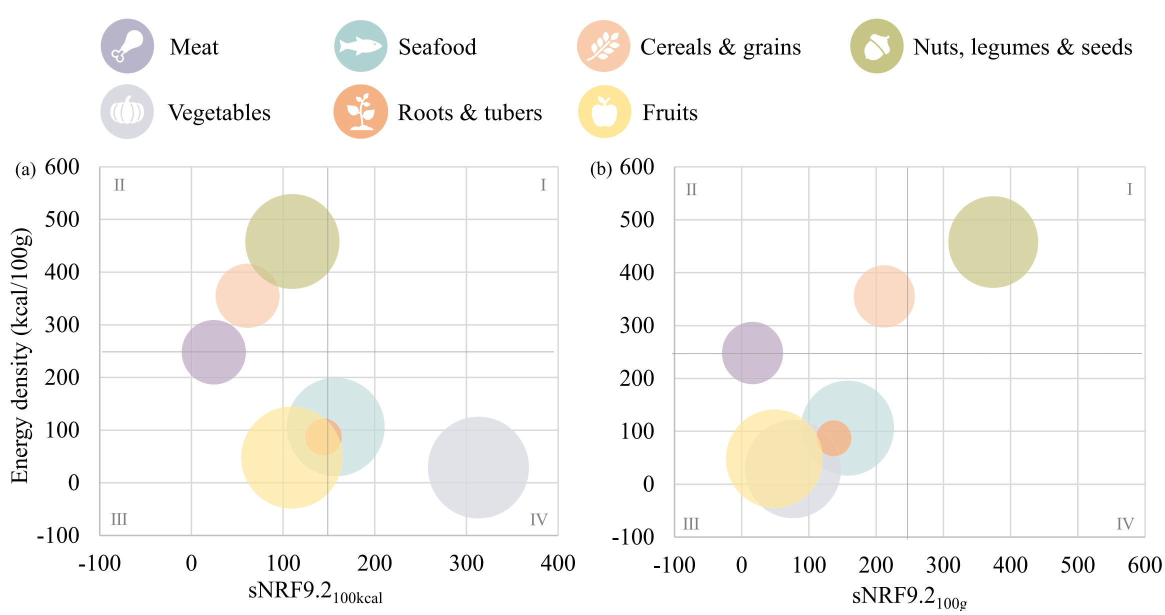

Fig. 2 Application of the sNRF9.2 model in different food categories. **a** Reference unit of100 kcal (sNRF9.2$_{100\ kcal}$). **b** Reference unit of 100 g (sNRF9.2$_{100\ g}$). The center of the circle is located at the average energy density (y-axis) and average sNRF9.2 score (x-axis) and the area correspond to the number of foods included of each group; the larger the circle, the greater the number of food products

and seeds at the top of the ranking, followed by cereals and grains, fish and seafood, and vegetables. In the sNRF9.2 scores without weighting, nuts and legumes still scored up to 79% higher than tubers or 87% higher than fruit. For virtually all the products assessed, the absence of capping led to the same results, as the amount of nutrients did not exceed the recommended daily allowance. However, for some foods, such as hazelnuts, the score was influenced by this variable, reaching higher values due to the large amount of vitamin E. In this case, an increase of the score of 32% was obtained due to the absence of truncation. On the other hand, the elimination of weighting factors balances the prioritization of foods by providing lower scores for all products, especially for those previously identified as most beneficial. Differences between scores of different food groups were substantially reduced: while there was a 162-point difference between nuts or legumes and cereals, when no weighting was applied, it decreased to 88 points. This variable also has an influence within the same food category, modifying the order of the most suitable foods (see Research Data). It is therefore advisable to apply weighting factors to justify more comprehensive rankings of foods according to the deficiencies to be satisfied.

3.2 Application of the model to "superfoods"

Figure 4 depicts the scores obtained for different "superfoods" by applying the sNRF9.2 model under a reference basis of 100g and 100kcal. Both scores followed a similar trend as that of conventional foods, with crops belonging to the nuts, legumes and seeds, and cereals and grains obtaining the highest $sNRF9.2_{100g}$ scores and vegetables, herbs and some fruits at the top of the $sNRF9.2_{100kcal}$ scores ranking. This statement further validates the nutritional model within its domain, aligning it with health recommendations and other models. Based on the mass reference, chia seeds (*Salvia hispanica*), bee pollen, turmeric (*Curcuma longa*), cocoa (*Theobroma cacao*), and flaxseeds (*Linum usitatissinum*) were identified as the most nutritious species, whereas moringa (*Moringa oleifera*), kale (*Brassica oleracea*), and cai berries (*Euterpe oleracea*) were by far the most beneficial on the basis of energy density. Generally, the $sNRF9.2_{100g}$ score for "superfoods" was above the average for conventional products from the same category. For instance, foods belonging to cereals and grains ranged from 337 to 587 as a consequence of the large amount of fiber and minerals, e.g., magnesium, calcium, or iron. Likewise, "superfruits" scores were between 48 and 234, with the minimum value coinciding with the average of common fruits. In addition, non-classified "superfoods," i.e., bee pollen and spirulina, reached $sNRF9.2_{100g}$ scores of 578 and 334, respectively, mainly caused by the concentrations of Fe, Zn, Mg, or vitamin E. It is worth noting that practically all the roots and tubers were below average (137), with the exception of turmeric, which tops the ranking for its concentration of fiber, vitamin E, and Zn. On the other hand, considering energy in the sNRF9.2 index significantly equaled the scores of "superfoods" and conventional foods from the same category, except for kale and cai, which were well outside the average, with scores of 502 and 546, respectively.

3.3 How can the environment-nutrition binomial influence decision-making?

As set out in Fig. 5, there was no correlation between nutrient composition and climate impacts, which was supported by a Pearson's correlation coefficient of − 0.08 that indicates that the variables do not have a linear dependence. Besides, a *p*-value of 0.65 suggested a high probability that the hypothesis that both variables are independent is true. A more detailed statistical assessment compressing a principal component analysis (PCA) and the determination of

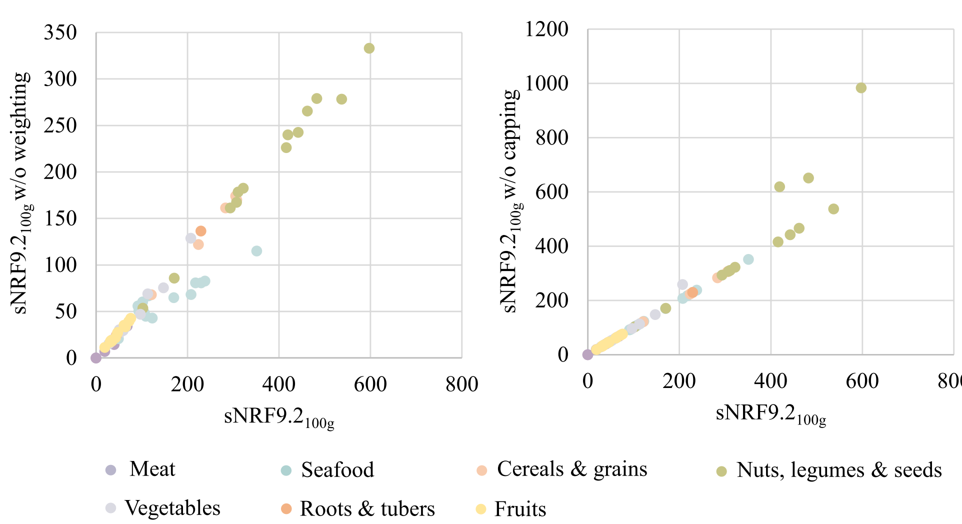

Fig. 3 Sensitivity of the $sNRF9.2_{100g}$ model. $sNRF9.2_{100g}$ scores were calculated without weighting factors and without capping

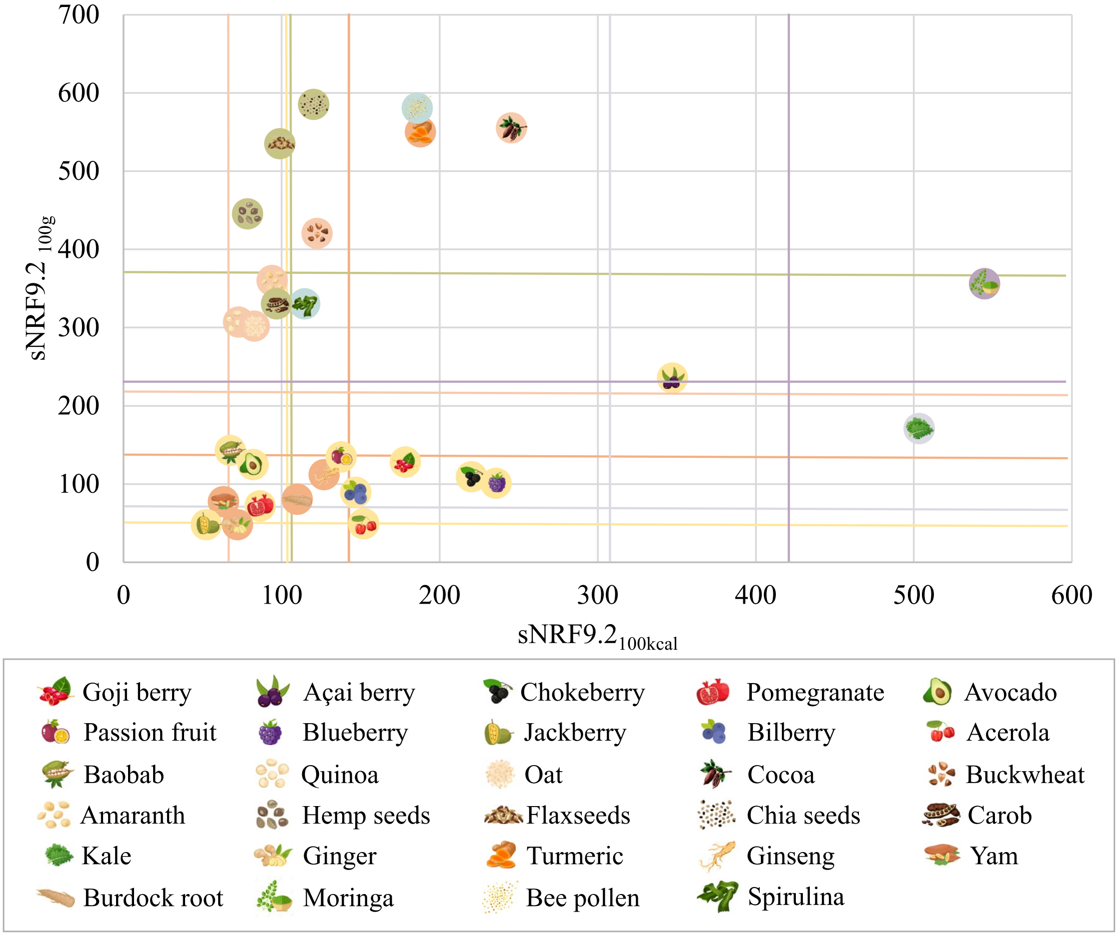

Fig. 4 Application of the sNRF9.2 model to different "superfoods" considering a mass and energy reference. The horizontal and vertical lines represent the average scores for conventional products in different categories: dark purple: meat, blue: fish and seafood, light pink: cereals and grains, green: nuts, legumes, and seeds, light purple: vegetables, dark pink: roots and tubers, yellow: fruits

other variables regarding correlations can be consulted in Research Data.

New patterns emerged as a result of the integration of both pillars and the modification of the food classification described in the previous sections. Most food categories were placed in the third quadrant (Fig. 5a), where GHG emissions are low, as are the nutrient levels contained in the products. This situation creates a conflict between climate and nutritional performance, where consumers must make rational choices, weighing whether a more nutritious but more polluting food or a more nutritionally limited but less GHG-emitting food is more desirable. However, delving deeper into the assessment of each individual product allows for a more thorough judgment. For instance, as shown in Fig. 5b, which reports GWP impacts per sNRF9.2, three of the four cereals are in the top half of the list, while the poor nutritional quality of rice places it at the bottom of the ranking, penalizing the average food group shown in Fig. 5a. In fact, oat and barley came in second and third positions, respectively, of the rankings, making a "superfood" one of the most suitable for consumption by considering both nutritional and climatic implications. The relatively low environmental impact of fruits as well as vegetables placed them in the middle of the food ranking, with impacts ranging from 0.19 (red pepper) to 99 g CO_2 eq./sNRF9.2 (bilberry). The same was true for fish and seafood, which had the rightmost position in the third quadrant (Fig. 5a); however, this was mainly due to the low GHG emissions of sardines, whereas all the other fish had rather low GHG emissions due to resource- and emission-intensive fishing activities (Ceballos-Santos et al. 2023). On the other hand, nuts, seeds, and legumes belonged to the fourth quadrant, representing the best alternative and enabling sustainable choices by boosting consumption. White beans, hazelnuts, and carob seeds were among the ten products with the best environmental profiles, with GWP impacts of $3.5{\cdot}10^{-2}$, 0.23, and 0.28 g CO_2 eq./sNRF9.2, respectively. The category "others" was situated at top of the fourth quadrant and included only dried spirulina,

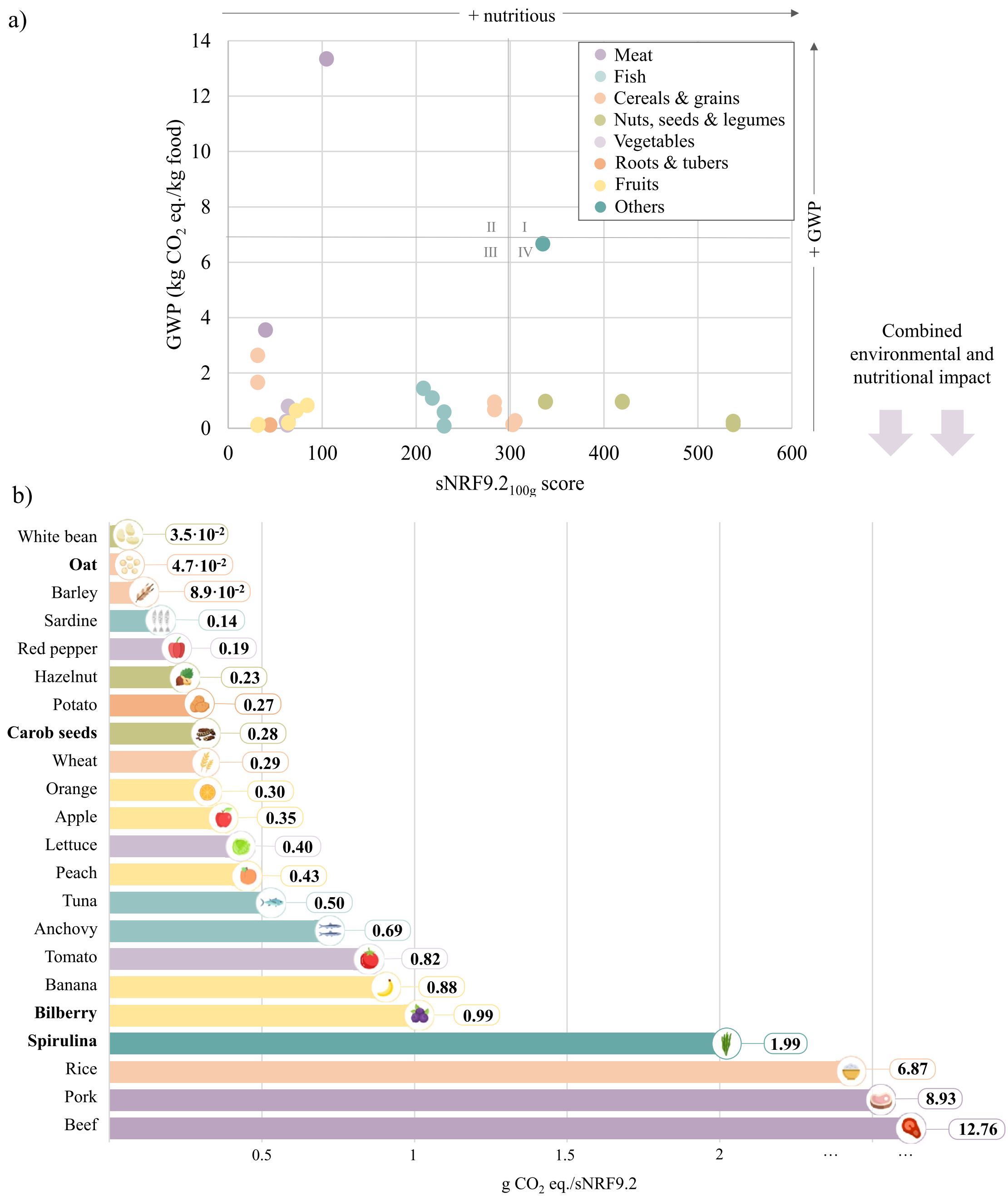

Fig. 5 Integrated nutritional and environmental impacts of foods. (**a**) Relationships between sNRF9.2$_{100g}$ scores and GWP impacts on different food groups and (**b**) rankings of foods according to their carbon footprint using the functional unit sNRF9.2. Products in bold represent "superfoods"

which means a relatively high nutrient density but also a high climate cost associated with its production and processing. Even greater is the impact of meat, which, together with its low sNRF9.2 score, puts the group in the second quadrant and sets pork and beef at the bottom of the list.

4 Limitations and discussion

The strong influence on sustainability outcomes arising from regional differences associated with localized nutrition and climate interactions, already demonstrated by

Green et al. (2021), has driven the development of this methodology. For this reason, the model can be considered a double-edged sword; its specificity can be seen as either a strength or a weakness. On the one hand, its applicability to the Spanish context provides more objective outcomes on which to base decision-making. However, one of the main limitations of the model lies precisely in this contextualization. The selection of qualifying nutrients and the use of weighting factors provides to the model a key feature to allow a rigorous prioritization of foods, but it is important to note that these factors need to be updated. They were estimated on the basis of the recommended daily intake, which usually remains constant, but also on the average intake of each nutrient by the population. In this study, the most recent data available have been used, albeit consumer habits are constantly evolving and so are the nutritional needs for consumers. For that reason, it is essential to consistently identify the deficient nutrients and recalculate the weighting factors when applying the model in future studies in order to know the food reality of the region and to be able to choose the foods that can best solve the nutritional issue.

In this line, although this approach can lead to the design of healthy and sustainable diets in other parts of the world, its robustness would be weakened if applied to other countries. Proof of this would be the comparison with NRF9.3, developed by Drewnowski (2009) based on the dietary guidelines for the U.S. population. This NP model, which applies a reference unit of 100 kcal, follows a fairly similar trend to that of sNRF9.2$_{100\ kcal}$, although in the Spanish version for tubers and fish, the values are closer to those of fruits, and overall, the scores are greater. This is mainly due to weighting factors and the consideration of different nutrients, for instance, potassium, vitamin C, or protein are included in the NRF9.3. The latter was incorporated into the NRF9.3 index, not because it is a deficient nutrient in the American diet but because a model without protein may have more limited utility. The proteins were considered for inclusion in sNRF9.2, as was the protein quality, according to the DIAAS (Digestible Indispensable Amino Acid Score), as this aspect has been identified as lacking and necessary in nutritional indices (McAuliffe et al. 2023). However, this option was discarded for two main reasons. First, if proteins are included as key or essential nutrients, other equally important ones, such as essential polyunsaturated fatty acids (alpha-linolenic or alpha-linoleic acids), would also have to be introduced. Second, given that the objective of the model, from a purely nutritional perspective, is to identify the foods that best meet the nutritional shortfalls of the Spanish population, including a nutrient that is currently overconsumed would weaken it, leading to less comprehensive results and confusing consumers in their decision making. Therefore, depending on the type of food to be assessed and on the goal of the model, the indicator could be modified to address this nutrient of interest, e.g., for specific products that stand out for this quality (alternative proteins) or for an indicator that aims to measure the overall health value of Spanish foodstuffs.

Another debatable aspect of the model design revolves around the consideration of disqualifying nutrients. This point is relevant due to the risk of a negative FU, and consequently of environmental impacts that can lead to a misinterpretation of avoided burdens, but also due to the contradiction that their inclusion may imply in terms of the representativeness of the food function, which is to nourish, not to harm (Green et al. 2023). In this study, the incorporation of nutrients to limit was based on the suitability of obtaining results that do not tend to prioritize energy-dense foods and that encompass all nutritional aspects of the food in a single score. However, depending on the study, another approach may be considered more appropriate. In some cases, such as junk food or sweets, nutrition hardly represents their function, so the consideration of detrimental nutrients as health impacts could be a suitable alternative. In this line, some studies highlight the importance of dietary metrics, such as DALY (Weidema and Stylianou 2020) and progress is being made in the development of methodological frameworks, as demonstrated by Scherer et al. (2024), which considers dietary risk factors based on the global burden of disease and provides guidance for its further development.

Regarding the practical application of the model, the sNRF9.2 is dependent mainly on the availability of data on both nutritional composition and environmental profiles. The nutritional content tables of some “superfoods” are not complete, hindering the task of compiling information for the calculation of the score. Moreover, in a first attempt to look at trends in the relationship between nutrition and the environment, only GWP was taken as a benchmark for comparison, which may lead to misinterpretations since it is only an individual metric of environmental sustainability. For future analysis with the application of this FU, the prioritization of products should be influenced by the most critical indicators addressing emissions or resource depletion in Spain, e.g., the water footprint or land use (Green et al. 2021), among others. It should also be noted that both environmental impacts and nutritional profiles can change either by the application of different cultivation techniques, processing methods or process improvements (Munné-Bosch and Bermejo 2024). Hence, the most sustainable product may vary depending on the characteristics of the system, as well as the data and methodological choices, which forces the development of more detailed and comprehensive assessments in this field.

5 Conclusions

Within the context of transforming the food sector and seeking methodologies to achieve a sustainable transition, this work represents an initial step toward advancing research. The development of the Spanish Nutrient Rich ("super") Food 9.2 model marks a significant progress in integrating nutritional and environmental considerations into national food systems. By addressing specific nutritional deficiencies in the Spanish population and evaluating environmental impacts of "superfoods," it provides a robust framework for informed decision-making: the sNRF9.2 model enables consumers, stakeholders, and policymakers to identify and promote foods that balance nutritional needs with environmental sustainability. As a contextualized tool, it sets a foundation for further refinement and adaptation to other regions, contributing to sustainable food security and health-oriented dietary strategies.

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Data availability Data available on request.

Declarations

Conflict of interest The authors declare no competing interests.

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