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Environmental and nutritional Life Cycle Assessment of novel foods in meals as transformative food for the future

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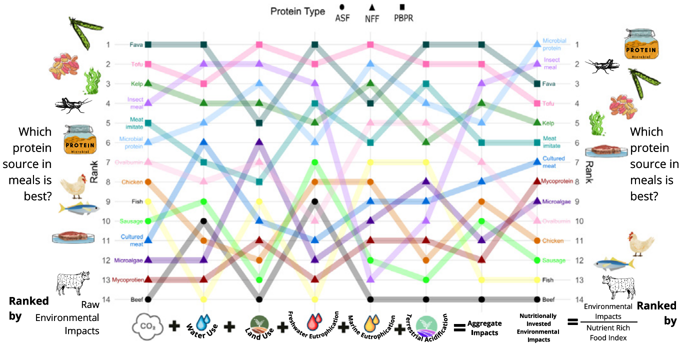
HIGHLIGHTS

- Novel foods offer options for healthier diets and sustainable food systems.
- Two nutritional LCAs were calculated for meals.
- Meals with novel, animal-source, and plant-based foods were ranked by impacts and nutrients.
- Meals with novel foods ranked best when impacts were integrated with nutrient richness.
- Novel foods offer nutritious, lower environmental impact animal protein substitutes.

GRAPHICAL ABSTRACT



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ABSTRACT

Sustainable diets are key for mitigating further anthropogenic climate change and meeting future health and sustainability goals globally. Given that current diets need to change significantly, novel/future foods (e.g., insect meal, cultured meat, microalgae, mycoprotein) present options for protein alternatives in future diets with lower total environmental impacts than animal source foods. Comparisons at the more concrete meal level would help consumers better understand the scale of environmental impacts of single meals and substitutability of animal sourced foods with novel foods. Our aim was to compare the environmental impacts of meals including novel/future foods with those of vegan and omnivore meals. We compiled a database on environmental impacts and nutrient composition of novel/future foods and modeled the impacts of calorically similar meals. Additionally, we applied two nutritional Life Cycle Assessment (nLCA) methods to compare the meals in terms of nutritional content and environmental impacts in one index. All meals with novel/future foods had up to 88 % less Global Warming Potential, 83 % less land use, 87 % less scarcity-weighted water use, 95 % less freshwater eutrophication, 78 % less marine eutrophication, and 92 % less terrestrial acidification impacts than similar meals with animal source foods, while still offering the same nutritional value as vegan and omnivore meals. The nLCA indices of most novel/future food meals are similar to protein-rich plant-based alternative meals and show fewer environmental impacts in terms of nutrient richness than most animal source meals. Substituting animal source foods with certain novel/future foods may provide for nutritious meals with substantial environmental benefits for sustainably transforming future food systems.

Abbreviations: ASF, animal source food; EU, Europe; FE, freshwater eutrophication; GHGEs, greenhouse gas emissions; GWP, Global Warming Potential; LCA, Life Cycle Assessment; LU, land use; MA, marine eutrophication; NF, Nutritional Footprint; NIEI, Nutritionally Invested Environmental Impact; NRF, Nutrient Rich Food; PBPR, plant-based protein-rich; TA, terrestrial acidification; WU, scarcity-weighted water use.

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1. Introduction

Given the mounting evidence of the need for health- and environment-related changes in food and nutrition practices (Johnston et al., 2014; Popkin, 2006; Willett et al., 2019), there is resounding recognition that dietary change can be a main driver of sustainability in food systems (M. A. Clark et al., 2019; M. Clark and Tilman, 2017; Hallström et al., 2015). More than one third of global greenhouse gas emissions (GHGEs) are attributed to the food system, taking into account the agricultural production, storage, transportation, processing, packaging, retail, consumption, and waste of foods (Crippa et al., 2021; IPCC, 2019). Calls for sustainability transformations in the food system have centered around production and consumption changes related mostly to livestock, either by improving livestock production system efficiencies (Röös et al., 2016; van Zanten et al., 2016) or greatly reducing intake of animal-source foods (ASFs) (Perignon et al., 2016; Vieux et al., 2018; Willett et al., 2019). Half of GHGEs from the production of food are attributed to livestock production (Xu et al., 2021), and diet optimization models consistently confirm the need to reduce ASF intake (Chaudhary and Krishna, 2019; Mazac et al., 2022; van Dooren et al., 2015; Wilson et al., 2019).

Novel food production technologies and future foods may provide nutritious alternatives while meeting multiple sustainability goals and providing for ‘risk-resilience’ in diets (Parodi et al., 2018; Tzachor et al., 2021). In European Union regulations, the term ‘Novel Food’ is defined as a “newly developed, innovative food, food produced using new technologies and production processes, as well as food which is or has been traditionally eaten outside of the EU” (European Commission, 2022). The novel foods presented in this paper are produced through novel production technologies that belong to ‘cellular agriculture’, where cells are cultured in vitro, and may act as substitutes for conventional ASF (e.g., cultured meat, microbial proteins, cultured plant cells) (Post et al., 2020). Due to their technological nascency, such novel foods fall under novel food regulatory schemes, but can be engineered to have similar nutritional, taste, and texture profiles as more conventional ASFs (Bryant and Barnett, 2020; Post et al., 2020; Siegrist and Hartmann, 2020).

Future foods offer options which are already consumed but may differ from more familiar ASF options in ‘western diets’ (e.g., insects, kelp). Future foods are defined in line with Parodi et al. (2018), where production and consumption are being scaled up out of environmental concerns (Parodi et al., 2018; Tzachor et al., 2021). Here, we combine these terms into the category of ‘Novel/Future Foods’ (NFFs) as foods through which, either by novel means and/or driven by sustainability concerns, may offer nutritious, potentially less environmentally impactful alternatives as ASF substitutions.

Current plant-based diets may have lower GHGEs than omnivore diets (Wilson et al., 2019), but vegan/vegetarian diets may not be necessarily of the highest nutritional quality (Vieux et al., 2013). It is therefore necessary to assess environmental impacts in terms of the nutritional function of foods. Several nutritional life cycle assessment (nLCA) methods exist to aggregate environmental impacts and nutritional quality of foods and meals into one, composite index (Green et al., 2021; Hallström et al., 2018; Lukas et al., 2016; Saarinen et al., 2017; Sonesson et al., 2019). Such consolidated, single environmental and nutritional indices allow for improved comparison and consumer comprehension—over that of direct environmental impacts and oversimplified comparisons on energy content, specific nutrients, or mass (Hallström et al., 2018; van Dooren et al., 2017; Weidema and Stylianou, 2020). Further application of such indices may lead to a better understanding of how the substitution of ASFs with NFFs can yield decreases in environmental impacts and meet nutritional quality thresholds.

Prior studies focusing on environmental impacts of NFFs compare impacts only at the product level (Järviö et al., 2021a; Järviö et al., 2021b; Smetana et al., 2015; Tuomisto et al., 2022). Whole diet optimizations have also examined the potential of replacing ASFs with NFFs in current European diets, demonstrating positive implications for meeting nutritional requirements with minimal environmental impact (Mazac et al., 2022). Yet, as the value of a diet depends on all foods consumed, often in the unit of a single meal, during a given day, it is important to compare nutritionally isometric meals (Lukas et al., 2016). Due to differences in nutritional content and to facilitate understanding of environmental impacts of foods in terms of a more familiar unit of consumption—the meal and not the more abstract ‘diet’, meal level comparisons are also needed to investigate the substitutability of ASFs with plant-based protein-rich (PBPR) alternatives and NFFs in future sustainable diets. Therefore, this work sought to answer: how do the environmental impacts—Global Warming Potential (GWP), scarcity-weighted water use (WU), land use (LU), freshwater eutrophication (FE), marine eutrophication (ME), and terrestrial acidification (TA)—of meals with NFFs compare to meals of similar nutritional content with ASF or PBPR alternatives? Further, how do the nLCA indices, considering health and environment dimensions, combined into one score, of meals with NFFs compare to vegan and omnivore meals?

2. Materials and methods

2.1. Meals

We sourced the original recipe for a nutritionally balanced, low-GHGE optimized meal from author correspondence with Eustachio Colombo et al. (2020). The original recipe was a chickpea patty with roasted root vegetables and a (soy-based) cream sauce (Eustachio Colombo et al., 2020). From that recipe, we composed fourteen alternative meals by altering the protein source of the patty in the original recipe with that of other PBPR alternatives (plant-based meat imitates and tofu), NFFs, or conventional ASFs (beef, chicken, pork sausage, and fish). See Supplementary Table 1 for product database with environmental impacts and nutrition composition by ingredient.

We selected seven NFFs to be included in the study since those products have the possibility to be produced in the future at-scale with the nutrient profiles to act as substitutes for conventional ASFs (Voutilainen et al., 2021). We also selected NFFs where the data for the production of these NFFs is currently available (Parodi et al., 2018; Post et al., 2020). NFFs included here are cultured meat, ovalbumin (produced using the fungus *Trichoderma reesei)*, microbial protein (hydrogen-oxidizing bacteria), microalgae (*Chlorella vulgaris*), insect meal (*Hermetia illucens*), kelp (*Saccharina latissima*), and mycoprotein.

Based on the proportions of food items in the original recipe, we adjusted each meal with a varying mass of the substitute proteins, carbs, and fat to match recommended daily intake proportions of total energy (%E) from protein (10–20%E), fat (25–40%E), and carbohydrates (45–60%E) (see Supplementary Table 2 for meal ingredients list and calculations). Due to the high protein content of most NFFs, many meals required more proportional energy from carbohydrates by the addition of ~10–100 g more potatoes compared to the original recipe, and a few meals required a slight reduction in fat energy from ~1–3 g less vegetable oil. From the original recipe, intended for children aged 10–12, we multiplied the mass of each food item in each meal by a ‘multiplier’—ranging from 1.75 to 4—for an adult portion size. Since we assumed a nutrient-rich meal provides about one third of the daily required energy (Lukas et al., 2016), the multiplier is needed for the meal to reach about one third (25–30 %) of the current average energy intake (2364 kcals/day) of average European adult diets (EFSA, 2018).

We include feasible upper consumption limits in the meal calculations for certain NFFs based on their nutrient content: microalgae, microbial protein, and kelp. For example, the upper limit on intake of microalgae is <10 g/day based on maximum iron content (Siva Kiran et al., 2015). For the remaining NFFs, we check that the intake is lower than the highest feasible amount of intake per day derived from the mean + 0.5 standard deviations of daily intake of a proxy product in average European diets (EFSA, 2018) (e.g., protein from ASF meat substituted by cultured meat). See Supplementary Table 3 for feasible consumption calculations. We also calculated the amino acid content of each meal. We then compared the amino acid profile of each meal to 33 % of the daily recommended intake of essential amino acids in the whole diet (EFSA, 2018).

2.2. Product database

2.2.1. Nutrient composition data

We linked each of the individual food items from the meal to data on product nutrient composition in the US Department of Agriculture (USDA) FoodData Central (EFSA, 2018; USDA, 2018). We obtained nutrient composition data of NFFs, or closely matching items, to the NFFs from the USDA FoodData Central or from published studies (see Supplementary Table 4 for NFFs nutrient data sources). Insect meal was *H. illucens* powder with nutrient data from edible insect proteins (de Castro et al., 2018; Montowska et al., 2019; Wang et al., 2005). Microalgae macronutrient data was from *C. vulgaris* nutrient composition (Koyande et al., 2019), and microalgae micronutrient data were from the USDA FoodData Central. All data for kelp, *S. latissima* was from USDA FoodData Central (USDA, 2018). Mycoprotein nutrient data was compiled of nutritional profiles of mycoproteins as meat substitutes (Hashempour-Baltork et al., 2020; Quorn Nutrition, 2020). Microbial protein nutrient data was from a direct analysis of the protein powder by the producer (Solar Foods Oy, 2019).

2.2.2. Environmental impact data

The environmental impacts of the ingredients were based on the life cycle assessment (LCA) method (Guinee et al., 2011; ISO, 2006). Our system boundaries were from cradle to consumer and included cooking at consumer. The LCA inventory data for food items in the meals included in current European diets was sourced from the AGRIBALYSE 3.1 LCA Database where the energy source had been changed from French average electricity to European (without Switzerland) average electricity mix (French Agency for Ecological Transition, 2020) using the OpenLCA 1.10.3 software (GreenDelta, 2007). The ReCiPe 2016 Midpoint (H) method (Huijbregts et al., 2017) was used to calculate the GWP (kg CO_2 equivalents), land use (m^2 arable cropland equivalents), terrestrial acidification (kg SO_2 equivalents), freshwater eutrophication (kg P equivalents), and marine eutrophication (kg N equivalents). The AWARE method (Boulay et al., 2018) was used to calculate scarcity-weighted water use (m^3) per gram of the food items. We selected these environmental impact categories as they are the most commonly used categories within assessments and comparisons of environmental impact of food products (Campbell et al., 2017; Crippa et al., 2021; Hallström et al., 2022; Humpenöder et al., 2022; Pikaar et al., 2018; Poore and Nemecek, 2018; Sillman et al., 2020). The functional unit was one meal, which represented the sum of the environmental impacts of each individual ingredient making up the meal.

Environmental impact data for the NFFs were obtained from LCAs in recently published literature (Järviö et al., 2021a; Järviö et al., 2021b; Smetana et al., 2017, 2019, 2021; Tuomisto et al., 2022). NFF environmental impacts were calculated using the ReCiPe midpoint and AWARE impact methods. Electricity consumption for all products produced in Europe was modeled using the European average (without Switzerland) electricity mix in the life cycle inventory. Scarcity-weighted water use was calculated in the article using the IMPACT World + Midpoint V0.04 method that relies on the AWARE method. The French non-irrigation characterization factor for the processing part (3.051) of the AWARE method was used to assess the impact of water use—for comparison, the European non-irrigation AWARE factor is 5.919 (Boulay et al., 2018).

We remodeled the microalgae product system with the SimaPro 9.1.0.11 PhD software package (Consultants, 2020) using the inventory data for the microalgae (*C. vulgaris* tubular photobioreactor) scenario provided. This allowed us to recalculate microalgae environmental impacts using the same impact method as the other products since the results were originally calculated using the IMPACT 2002+ method (Smetana et al., 2017). Environmental impacts for mycoprotein were estimated by creating a model based on the inputs reported by Smetana et al. (2021). We assumed cultured meat has a dry matter content of 30 % and used the same LCA methods as above cultured meat combined scenario in Tuomisto et al. (2022). LCA impacts of dried kelp, or sea belt, were from the AGRIBALYSE 3.1 database. For the insect meal, we used *H. illucens* insect protein meal attributional LCA with IMPACT 2002+ method (Jolliet et al., 2003) mean data only since the material provided in publications and by author correspondence was not sufficient for recalculating the environmental impacts with ReCiPe (Smetana et al., 2019).

We added aspects of the life cycle not considered in the original LCA studies of the NFFs (factory to consumer, without cooking) to match the system boundaries of the other meal ingredients; these additional steps included transportation, packaging, and retail environmental impacts. For protein powder-like NFF products—microalgae, ovalbumin, insect meal, and microbial protein, we added the required steps similar to those of dried nuts and for cultured meat those of minced meat.

We then modeled each meal, calculating the environmental impacts from terrestrial acidification, marine eutrophication, freshwater eutrophication, scarcity-weighted water use, land use, and GWP and nutritional content for each meal based on the mass of each food item in the adjusted base recipe.

2.3. Nutritional Footprint calculations

We calculated the Nutritional Footprint (NF) of each meal adapting the methods of Lukas et al. (2016) as the first nLCA method. nLCA is a nascent method to integrate nutrient richness and environmental LCA factors and accounts for the fact that food serves a nutritional function as well as having direct environmental impacts (Saarinen et al., 2017; Weidema and Stylianou, 2020). The health and environment subtotals are calculated per meal with the relevant nutrition and environmental impact values for each ingredient in the meal. We calculated health subtotals (NF_{health}) with the health indicators of total energy intake (kcal), sodium (g), dietary fiber (g), and saturates (g) of each meal. Environment subtotals (NF_{envi}) were calculated for each meal with environmental indicators of GWP, scarcity-weighted water use, land use, freshwater eutrophication, marine eutrophication, and terrestrial acidification. NF_{health} and NF_{envi} were calculated, respectively, adapted from Lukas et al. (2016):

$$NF_{health} = \frac{kcal_{effect} + fiber_{effect} + sodium_{effect} + saturates_{effect}}{4}$$

$$NF_{envi} = \frac{GWP_{effect} + WU_{effect} + LU_{effect} + TA_{effect} + FE_{effect} + ME_{effect}}{6}$$

This step synthesized the health and environment indicators separately as to calculate the effect level for each and allowed for an equitable ranking of all indicators in relation to each other. Calculation of these aggregated levels for NF_{health} and NF_{envi} gives equal weight to each of the components in the scores; in other words, all nutrients and environmental impact categories contribute equally to the final respective scores. Ultimately, to calculate the final NF (NF_{meal}), the health and environment effect levels were summed and averaged and given as one value between 1 and 3 for each meal, adapted from Lukas et al. (2016):

$$NF_{meal} = \frac{NF_{health} + NF_{envi}}{2}$$

For a qualitative ranking, and to comprehend the final NF_{meal} value for each meal, we reproduced Lukas et al.'s (2016) ranking of 'low', 'medium', or 'high'. For the resulting NF_{meal} scores, low impact was between 1 and 1.6, medium <1.6 and >2.2, and high impact between 2.2 and 3. Lukas et al. (2016) determined these impact rankings from the threshold levels of health and environmental indicators; we extended these environmental impact reduction thresholds for the three additional impacts (TA, FE, and ME) following recommendations from previous literature (Campbell et al., 2017; Hallström et al., 2022) (see Supplementary Table 5 for calculations). The health and environment subtotals were transferred into effect levels for each indicator by their respective threshold values.

Threshold values are calculated from current sustainable and healthy diet recommendations. For health thresholds, low impact, or healthy levels of intake were the current dietary recommendations, and high impact, or unhealthy intake levels, were current intake values. In Lukas et al.'s estimation, that meant that all current intake values were unhealthier than current recommendations. Since we calculated the meals to be within 25–30 % of daily total energy intake, we also recalculated the low impact threshold for kcal to be ≤30 % total energy intake of the current average European diet. The effect level for each health and environment impact was the translation of their respective threshold values into an effect level from 1 to 3, where low was 1, medium 2, and high 3. For example, caloric intake per meal is <709 kcals for low impact (level 1), 709–830 kcals for medium (level 2) and > 830 kcals for high impact (level 3). For environment thresholds, low impact was a 100–50 % reduction and high impact was a 50–25 % reduction from current diet impacts. We recalculated the environment threshold levels from Lukas et al. (2016) based on the ReCiPe and AWARE impact methods (see Supplementary Table 5 for the recalculations of threshold levels and Supplementary Table 6 for each indicator and the total NF).

2.4. Nutritionally Invested Environmental Impact calculations

We calculated a Nutritionally Invested Environmental Impact (NIEI) value per meal as a second nLCA (Green et al., 2021). The NIEI of Green et al. (2021) is a method which integrates environmental impacts with nutrient richness scores based on recommended daily allowances (RDAs) or adequate intakes (AI) of nutrients per person per day. In this way, the NIEI gives environmental impacts in terms of nutrient richness functional units.

We adapted the methods of Green et al.'s (2021) nLCA for individual food products to calculate the Nutrient Rich meal ($\mathrm{NR}_{\mathrm{meal}}$) score:

$$\mathrm{NR}_{meal} = \frac{1}{n} \times \sum_{i=1}^{n} \left(\frac{\frac{i_j}{calories_j} \times \frac{1}{3} kcal}{\frac{1}{3}\ RDA_i\ or\ AI_i} \right)$$

where n = the total number of nutrients with positive health association, i = value of individual nutrients with positive health association, j = meal, $kcal$ = total energy intake per day (kcal), RDA = Recommended Daily Allowance, and AI = Adequate Intake. $\mathrm{NR}_{\mathrm{meal}}$ was calculated over 24 positive nutrients in the meals (see Supplementary Table 7 for list of daily recommended values of each nutrient). These 24 nutrients were included in the $\mathrm{NR}_{\mathrm{meal}}$ as the data availability allowed for comparison with given recommendations.

For example, for the fava bean meal containing 15.7 g of fiber and 594 kcal; we considered the required 25 g/day of fiber as the recommended adequate intake and 2365 kcal/person/day as the value of total daily energy intake. Then, both requirements were multiplied by 1/3rd to calculate the approximately required amount of fiber and kcal for each meal:

$$NR_{Fava\ meal} = \frac{1}{n} \times \sum_{i=1}^{n} \left(\frac{\frac{15.7\ \mathrm{g\ fiber}}{594\ kcal} \times \frac{1}{3} \cdot 2365\ kcal/day}{\frac{1}{3} \cdot 25\ g/day} \right) + nutrient_2 + \ldots + nutrient_n$$

This is repeated for each of n nutrients of positive health association and the total sum divided by n nutrients, yielding the final $\mathrm{NR}_{\mathrm{meal}}$ value for each meal.

We then calculated Green et al.'s (2021) Limiting nutrients ($\mathrm{LIM}_{\mathrm{meal}}$) score adapted to whole meals:

$$LIM_{meal} = \frac{1}{n} \times \sum_{i=1}^{n} \left(\frac{\frac{i_j}{calories_j} \times \frac{1}{3} kcal}{\frac{1}{3}\ MRV_i} - 1 \right)$$

where n = the total number of nutrients with negative health association, i = nutrients with negative health association, j = meal, MRV = Maximal Reference Values; if $\mathrm{LIM}_{\mathrm{meal}} < 0$, we set $\mathrm{LIM}_{\mathrm{meal}} = 0$. This was calculated over 4 nutrients to limit in the meals—sodium and total polyunsaturated, monounsaturated, and saturated fatty acids. These four $\mathrm{LIM}_{\mathrm{meal}}$ nutrients were selected as they have set upper limits in recommendations.

We then calculated the Nutrient Rich Food Index meal ($\mathrm{NRF24.4}_{\mathrm{meal}}$), also adapted from Green et al. (2021), considering the multiple recommended and limiting nutrients in a single index with the single meal as the reference unit. Capping was not used for correcting the intake levels of nutrients at 100 % of recommended intake levels or levels to limit; it has been asserted that capping should not be used for analyzing the nutritional quality of meals since dietary context must be included (Hallström et al., 2018). The $\mathrm{NRF24.4}_{\mathrm{meal}}$ is comparable to the $\mathrm{NF}_{\mathrm{health}}$ score:

$$NRF24.4_{meal} = NR_{meal} - LIM_{meal}$$

Next, we calculated the Nutritionally Invested Environmental Impact meal ($\mathrm{NIEI}_{\mathrm{meal}}$) value also adapted from Green et al.'s (2021) score for meals. We separately calculated a NIEI score for each environmental impact considering the total impact of each meal and using the $\mathrm{NRF24.4}_{\mathrm{meal}}$ as the denominator, yielding a NIEI for GWP (NIEI $\mathrm{GWP}_{\mathrm{meal}}$), scarcity-weighted water use (NIEI $\mathrm{WU}_{\mathrm{meal}}$), land use (NIEI $\mathrm{LU}_{\mathrm{meal}}$), terrestrial acidification (NIEI $\mathrm{TA}_{\mathrm{meal}}$), freshwater eutrophication (NIEI $\mathrm{FE}_{\mathrm{meal}}$), and marine eutrophication (NIEI $\mathrm{ME}_{\mathrm{meal}}$). We normalized the environmental impact values of each meal by dividing the value of the impacts in each meal by the total observed (obs) impact in the current European diet as $\mathrm{GWP}_{\mathrm{obs}}$, $\mathrm{WU}_{\mathrm{obs}}$, $\mathrm{LU}_{\mathrm{obs}}$ (Mazac et al., 2022) and $\mathrm{TA}_{\mathrm{obs}}$, $\mathrm{FE}_{\mathrm{obs}}$, $\mathrm{ME}_{\mathrm{obs}}$ (Notarnicola et al., 2017) (observed values can be found in Supplementary Table 5):

$$NIEI\ GWP_{meal} = \frac{\mathrm{GWP}_{meal}/\mathrm{GWP}_{obs}}{NRF24.4_{meal}}$$

$$NIEI\ WU_{meal} = \frac{\mathrm{WU}_{meal}/\mathrm{WU}_{obs}}{NRF24.4_{meal}}$$

$$NIEI\ LU_{meal} = \frac{\mathrm{LU}_{meal}/\mathrm{LU}_{obs}}{NRF24.4_{meal}}$$

$$NIEI\ TA_{meal} = \frac{\mathrm{TA}_{meal}/\mathrm{TA}_{obs}}{NRF24.4_{meal}}$$

$$NIEI\ FE_{meal} = \frac{\mathrm{FE}_{meal}/\mathrm{FE}_{obs}}{NRF24.4_{meal}}$$

$$NIEI\ ME_{meal} = \frac{\mathrm{ME}_{meal}/\mathrm{ME}_{obs}}{NRF24.4_{meal}}$$

An aggregated impacts (Agg $\mathrm{Impact}_{\mathrm{meal}}$) value was calculated to show the total of all environmental impacts without the nutritional component included. The Agg $\mathrm{Impact}_{\mathrm{meal}}$ value is comparable to the $\mathrm{NF}_{\mathrm{envi}}$ score:

$$Agg\ Impact_{meal} = \mathrm{GWP}_{meal}/\mathrm{GWP}_{obs} + \mathrm{WU}_{meal}/\mathrm{WU}_{obs} + \mathrm{LU}_{meal}/\mathrm{LU}_{obs} + \mathrm{TA}_{meal}/\mathrm{TA}_{obs} + \mathrm{FE}_{meal}/\mathrm{FE}_{obs} + \mathrm{ME}_{meal}/\mathrm{ME}_{obs}$$

Finally, to compare the NIEI value with the aggregated NF we took the average of the separate impact NIEI values per meal:

$$NIEI_{meal} = \frac{\mathrm{NIEI\ GWP}_{meal} + \mathrm{NIEI\ WU}_{meal} + \mathrm{NIEI\ LU}_{meal} + \mathrm{NIEI\ TA}_{meal} + \mathrm{NIEI\ FE}_{meal} + \mathrm{NIEI\ ME}_{meal}}{6}$$

3. Results

3.1. Meal environmental impact indicators

The total, respective environmental impacts in GWP, scarcity-weighted water use, land use, freshwater eutrophication, marine eutrophication, and terrestrial acidification of all meals are comparable, with notable exceptions in the beef and fish meals (Fig. 1). The beef meal had the largest GWP, land use, marine eutrophication, and terrestrial acidification impacts

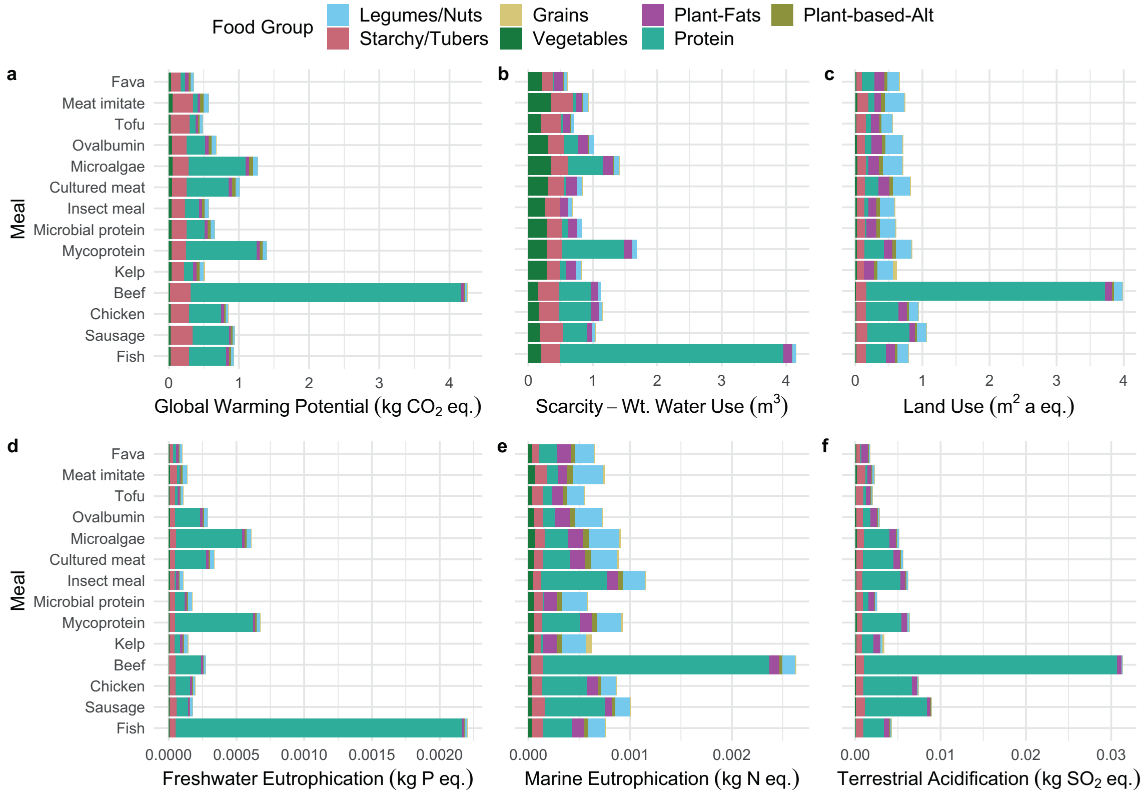


Fig. 1. Impacts by meal. a. Global Warming Potential (GWP; in kg CO_2 equivalents), b. scarcity-weighted water use (m^3), c. land use (m^2 arable equivalents), d. freshwater eutrophication (kg P equivalents), e. marine eutrophication (kg N equivalents), and f. terrestrial acidification (kg SO_2 equivalents) for each meal by food group; the meal is a protein patty with roasted root vegetables (potatoes, sweet potatoes, and carrots) and a plant-based alternative (soy) cream sauce.

and the second largest GWP. The fish meal had the largest scarcity-weighted water use and freshwater eutrophication impacts.

All PBPR alternatives and NFF meals had 87–92 % less GWP than the beef meal. The other ASF meals, chicken, fish, and sausage, had 78–80 % less GWP than the beef meal. PBPR alternative and NFF meals had 66–85 % less impact from scarcity-weighted water use than the fish meal. Other ASF meals had 72–75 % less impact from scarcity-weighted water use than the fish meal. PBPR alternatives, NFFs, and ASF meals had 81–86 %, 79–86 %, and 73–80 % less land use than the beef meal, respectively. PBPR alternatives had 94–95 %, NFFs had 69–95 %, and the other ASFs had 88–92 % less freshwater eutrophication potential than the fish meal. PBPR alternatives, NFFs, and other ASF meals had 71–79 %, 56–78 %, and 62–71 % less marine eutrophication potential than the beef meal, respectively. PBPR alternatives, NFFs, and ASF meals had 93–94 %, 80–92 %, and 71–87 % less terrestrial acidification potential than the beef meal, respectively (see Supplementary Table 2 for impacts by ingredient and meal).

3.2. Meal healthy nutrition indicators

Total energy of all meals ranged from 594 to 674 kcal (Fig. 2). Protein ranged from 16 to 32 g for all meals. Total fat in all meals ranged from 23 to 30 g. In all meals, carbohydrates ranged from 70 to 97 g. All meals remained within 25–30 % of daily intake of total energy (591–709 kcal/day) and within 10–20 % of total energy (%E) from protein, 25–40%E from fat, and 45–60%E from carbohydrates (see Supplementary Table 2 for nutrient content by ingredient and meal). All meals exceeded 33 % of the daily recommended amount of essential amino acids except for the kelp and fava meals, which were 0.03 g/day (13 %) and 0.06 g/day (26 %) short of the recommended amount of methionine, respectively (see Supplementary Table 8 and Supplementary Fig. 1 for amino acid comparisons by meal). The amino acid content of the meals ranged from 74 to 536 % of one third of the recommended amount of each essential amino acid per day.

3.3. Meal Nutritional Footprints

Using the method by Lukas et al. (2016), all meals had a low to medium total NF (NF_{meal}) when all nutritional and environmental indicators impact categories were combined (Table 1). Additionally, all meals had a low health (NF_{health}) effect level (meaning healthy), due to the fact that each meal was already energetically pre-balanced and designed to be a 'healthy meal'. Most meals had low environmental (NF_{envi}) effect levels, with the exception of microalgae, mycoprotein, fish, and beef meals, which had medium NF_{envi} effect levels. The microalgae and mycoprotein meals had a medium NF_{envi} effect level due to medium GWP, scarcity-weighted water use, freshwater eutrophication, and marine eutrophication effect levels. The chicken, fish, and sausage ASF meals had a low NF_{meal} effect level, and the beef meal had a medium NF_{meal} and medium NF_{envi} effect level, due to high GWP and land use values. The freshwater and marine eutrophication effects for all meals were in the medium range since the low threshold is a 100 % reduction in both eutrophication potentials.

3.4. Meal Nutritionally Invested Environmental Impacts

In terms of the Nutrient Rich food index ($NRF24.4_{meal}$), microbial protein and mycoprotein meals had the highest $NRF24.4_{meal}$ values—higher values mean more nutritious meals—due to their high positive Nutrient Richness (NR_{meal}) and comparably few nutrients to limit (LIM_{meal}). The ovalbumin, sausage, and beef meals had the lowest $NRF24.4_{meal}$ values due to their low NR_{meal} compared to high LIM_{meal} (Table 2). When the $NRF24.4_{meal}$ was used to compare NIEI by GWP (NIEI GWP_{meal}), the beef meal had the highest ratio of GWP to $NRF24.4_{meal}$ and the microbial protein meal the lowest. Lower ratios mean fewer environmental impacts

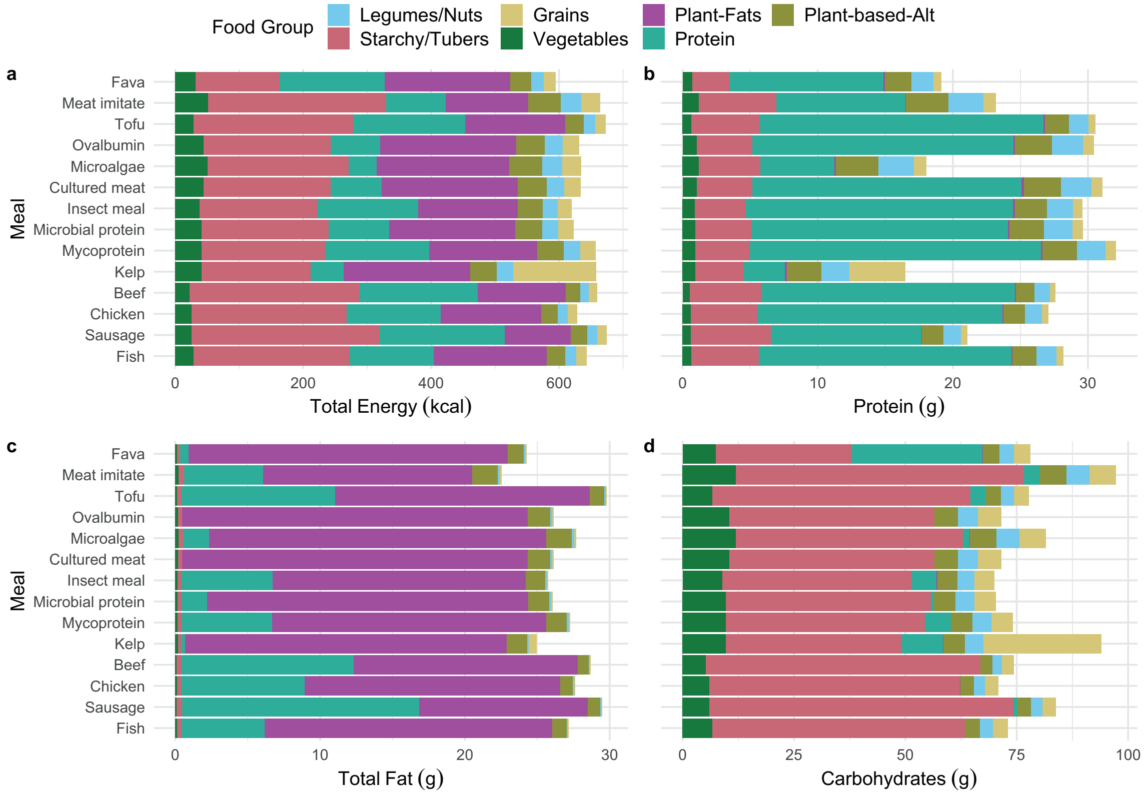


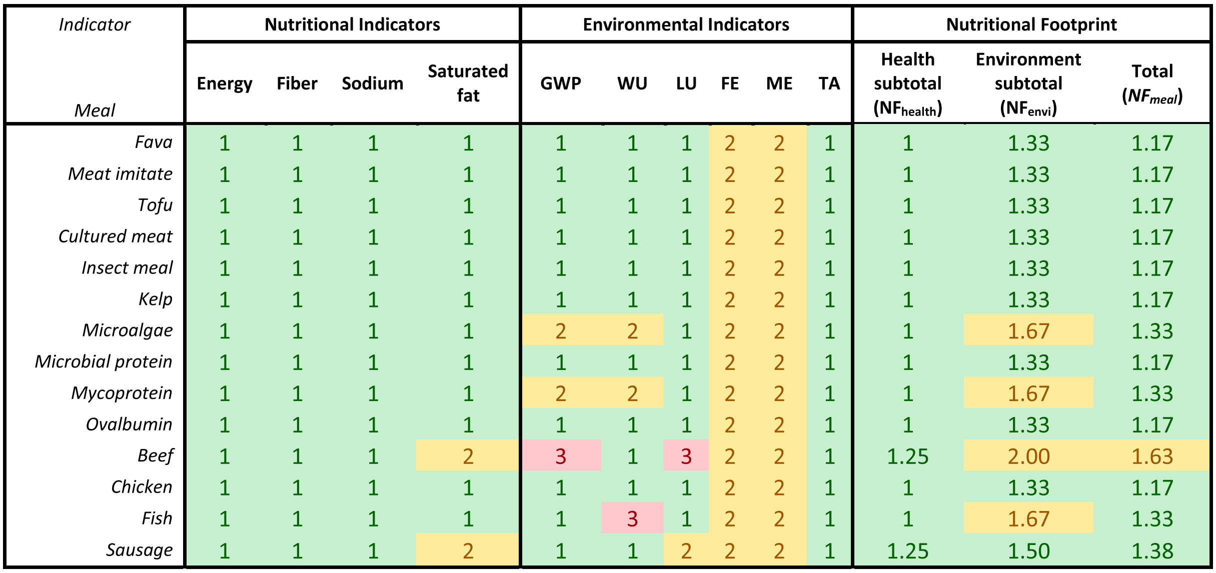
Fig. 2. Macronutrients by meal. a. total energy (kcal), b. protein (g), c. total fat (g), and d. carbohydrates (g) for each meal by food group.

and higher nutrient richness. The beef meal also had the highest land use to NRF24.4$_{meal}$ (NIEI LU$_{meal}$), marine eutrophication to NRF24.4$_{meal}$ (NIEI ME$_{meal}$), and terrestrial acidification to NRF24.4$_{meal}$ (NIEI TA$_{meal}$) ratios, and the microbial protein meal the lowest. In terms of scarcity-weighted water use to NRF24.4$_{meal}$ (NIEI WU$_{meal}$) and freshwater eutrophication to NRF24.4$_{meal}$ (NIEI FE$_{meal}$), the fish meal had the highest ratios and microbial protein the lowest.

The aggregated environmental impact value (Agg Impact$_{meal}$) revealed that the beef and fish meals had the most and second most aggregated environmental impacts, while the fava bean and tofu meals had the fewest,

Table 1

Nutritional and environmental indicator effect levels (1–3), and calculated health (NF$_{health}$) and environment subtotals (NF$_{envi}$) and total Nutritional Footprint (NF$_{meal}$) effect level by meal: Low impact (green; L ≤ 1.6), Medium impact (yellow; M > 1.6 and < 2.2), and High impact (red; H ≥ 2.2); Global Warming Potential (GWP), scarcity-weighted water use (WU), land use (LU), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial acidification (TA). Note: effect levels calculated from established nutritional and environmental thresholds, adapted to match environmental impact assessment methods for environmental indicators, from Lukas et al. (2016).



Indicator	Nutritional Indicators				Environmental Indicators						Nutritional Footprint		
Meal	Energy	Fiber	Sodium	Saturated fat	GWP	WU	LU	FE	ME	TA	Health subtotal (NF$_{health}$)	Environment subtotal (NF$_{envi}$)	Total (*NF$_{meal}$*)
Fava	1	1	1	1	1	1	1	2	2	1	1	1.33	1.17
Meat imitate	1	1	1	1	1	1	1	2	2	1	1	1.33	1.17
Tofu	1	1	1	1	1	1	1	2	2	1	1	1.33	1.17
Cultured meat	1	1	1	1	1	1	1	2	2	1	1	1.33	1.17
Insect meal	1	1	1	1	1	1	1	2	2	1	1	1.33	1.17
Kelp	1	1	1	1	1	1	1	2	2	1	1	1.33	1.17
Microalgae	1	1	1	1	2	2	1	2	2	1	1	1.67	1.33
Microbial protein	1	1	1	1	1	1	1	2	2	1	1	1.33	1.17
Mycoprotein	1	1	1	1	2	2	1	2	2	1	1	1.67	1.33
Ovalbumin	1	1	1	1	1	1	1	2	2	1	1	1.33	1.17
Beef	1	1	1	2	3	1	3	2	2	1	1.25	2.00	1.63
Chicken	1	1	1	1	1	1	1	2	2	1	1	1.33	1.17
Fish	1	1	1	1	1	3	1	2	2	1	1	1.67	1.33
Sausage	1	1	1	2	1	1	2	2	2	1	1.25	1.50	1.38

Table 2

Nutrient Rich (24 positive nutrients) (NR_{meal}) and Limiting Nutrient (4 nutrients to limit) (LIM_{meal}) indices to calculate Nutrient Rich Food ($NRF24.4_{meal}$) index by meal; Nutritionally Invested Environmental Impact indices for Global Warming Potential (NIEI GWP_{meal}), scarcity-weighted water use (NIEI WU_{meal}), land use (NIEI LU_{meal}), freshwater eutrophication (NIEI FE_{meal}), marine eutrophication (NIEI ME_{meal}), and terrestrial acidification (NIEI TA_{meal}) calculated from each impact in terms of their $NRF24.4_{meal}$, respectively; NIEI calculated per meal with the aggregated, averaged NIEI (NIEI Agg $Impact_{meal}$) of all six impacts ($NIEI_{meal}$).

Meal	*NR_{meal}*	*LIM_{meal}*	*$NRF24.4_{meal}$*	*NIEI GWP_{meal}*	*NIEI LU_{meal}*	*NIEI WU_{meal}*	*NIEI FE_{meal}*	*NIEI ME_{meal}*	*NIEI TA_{meal}*	*NIEI Agg $Impact_{meal}$*	*$NIEI_{meal}$*
Beef	3.01	0.89	2.12	0.30	0.32	0.07	2.93E-04	1.03E-04	1.54E-02	1.50	0.12
Chicken	3.33	1.00	2.33	0.06	0.07	0.07	1.93E-04	3.12E-05	3.32E-03	0.45	0.03
Fish	3.30	1.02	2.28	0.06	0.06	0.24	2.20E-03	2.78E-05	1.94E-03	0.84	0.06
Sausage	3.25	1.14	2.11	0.07	0.09	0.07	1.91E-04	3.98E-05	4.44E-03	0.47	0.04
Cultured meat	3.97	1.09	2.88	0.05	0.05	0.04	2.67E-04	2.57E-05	2.04E-03	0.41	0.02
Insect meal	3.64	0.84	2.80	0.03	0.04	0.03	8.74E-05	3.45E-05	2.31E-03	0.28	0.02
Kelp	3.71	1.17	2.54	0.03	0.04	0.04	1.32E-04	2.05E-05	1.39E-03	0.30	0.02
Microalgae	4.13	1.05	3.09	0.06	0.04	0.06	4.49E-04	2.45E-05	1.74E-03	0.51	0.03
Microbial protein	6.89	1.06	5.82	0.02	0.02	0.02	6.78E-05	8.40E-06	4.59E-04	0.32	0.01
Mycoprotein	4.47	0.89	3.59	0.06	0.04	0.06	4.29E-04	2.15E-05	1.85E-03	0.59	0.03
Ovalbumin	3.17	1.07	2.10	0.05	0.06	0.07	3.16E-04	2.91E-05	1.44E-03	0.36	0.03
Fava	3.15	0.88	2.27	0.02	0.05	0.04	1.02E-04	2.39E-05	7.98E-04	0.25	0.02
Meat imitate	3.67	0.86	2.81	0.03	0.04	0.04	1.12E-04	2.23E-05	8.49E-04	0.34	0.02
Tofu	3.50	1.17	2.33	0.03	0.04	0.04	1.04E-04	1.97E-05	9.06E-04	0.27	0.02

respectively. However, when the overall $NIEI_{meal}$ value is calculated for each meal, which includes respective $NRF24.4_{meal}$ values, the beef and fish meals have the highest and second highest ratios while the microbial protein and insect meals have the lowest and second lowest ratios. The $NIEI_{meal}$ ratio is higher in all ASF meals than the NFFs and PBPR alternatives meals.

When ranked from best (rank = 1) to worst (rank = 14) in terms of Agg $Impact_{meal}$ or $NIEI_{meal}$ score PBPR meals ranked consistently highest, ASF meals consistently lowest, and NFF meal rankings varied widely (Fig. 3). ASF meals ranked consistently in the low to middle range and much worse when the NRF24.4 index was included. The beef, chicken, fish, and sausage meals ranked from 7th to 14th when ranked by each environmental impact separately, 9th to 14th when ranked by Agg $Impact_{meal}$, and in the last four places (12th–14th) when ranked by $NIEI_{meal}$. PBPR meals ranked consistently in the middle to high range across environmental impacts and in the middle when NRF24.4 was included. PBPR meals ranked from 1st to 6th across all environmental impacts, with the exception of meat imitate in 7th for scarcity-weighted water use and 8th for land use. The fava bean, tofu, and meat imitate meals ranked 3rd, 4th, and 5th when ranked by $NIEI_{meal}$, respectively. There was much more inconsistency across the rankings in the NFF meals, but NFF meals ranked better when considering their nutritional composition. NFF meals ranked between 2nd and 13th across all environmental impacts and from 1st to 10th when ranked by $NIEI_{meal}$.

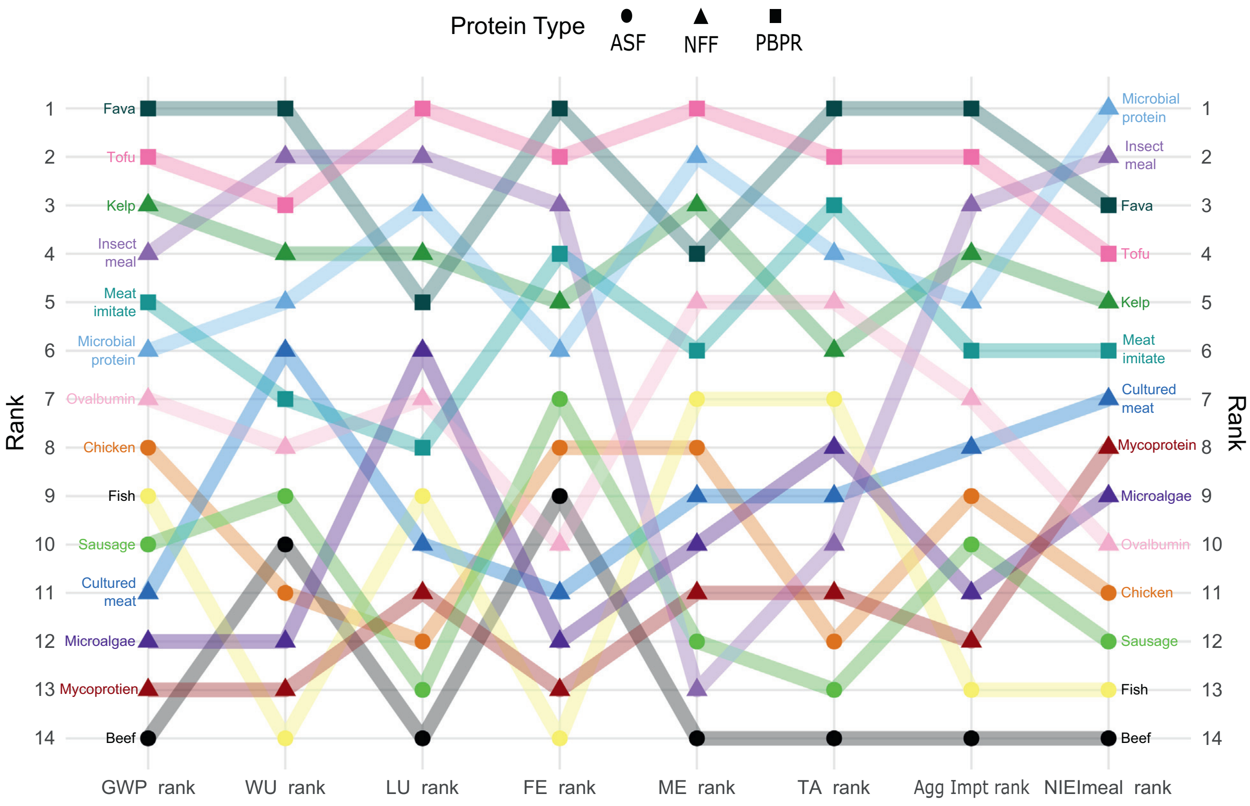


Fig. 3. Rankings of meals by total environmental impacts and combined nutritional and environmental impact index (NIEImeal). Global Warming Potential (GWP), land use (LU), water use (WU), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial acidification (TA), total aggregated impacts (Agg Impact), and combined Nutritionally Invested Environmental Impact (NIEImeal) score (average of all impacts to Nutrient Rich Food index ratio).

The ranking of the meals changed depending on NRF24.4$_{\text{meal}}$, and the NFF meals show the most dramatic changes in rank based on their NRF24.4$_{\text{meal}}$ scores. For example, sausage, fish, and chicken meals ranked better than microalgae, mycoprotein, and cultured meat meals in total GWP, but these ASF were the worst of all meals aside from beef in the NIEI$_{\text{meal}}$ score rankings. The insect meal ranked 13th and 10th in marine eutrophication and terrestrial acidification, respectively, but ranked between 2nd and 4th by all other environmental impacts, Agg Impact$_{\text{meal}}$, and the NIEI$_{\text{meal}}$ score. Microbial protein ranked 6th in total GWP and freshwater eutrophication, 5th in scarcity-weighted water use and Agg Impact$_{\text{meal}}$, 3rd in total land use, 2nd in marine eutrophication, and moved into 1st with the NIEI$_{\text{meal}}$ score. Meals that consistently ranked highest, interchangeably amongst 1st to 6th, were the kelp, tofu, microbial protein, and fava bean meals.

3.5. Comparison of nLCA indices

Comparing the nLCA indices which combine the environment and health aspects of the meals, most meals converged on the low NF$_{\text{meal}}$ and low NIEI$_{\text{meal}}$ (Fig. 4). The beef meal stands out as the meal with the highest NF$_{\text{meal}}$ and NIEI$_{\text{meal}}$ values; the sausage and chicken meals had low NF$_{\text{meal}}$ and but moderately higher NIEI$_{\text{meal}}$ values. The mycoprotein NFF meal stood out with a low but still comparatively higher NF$_{\text{meal}}$ value due to their high environmental impacts. Though, none of the meals scored in the high NF$_{\text{meal}}$ range, suggesting that there is a fairly large variance amongst the environmental impact values such that, when averaged, the tradeoffs amongst the different environmental impacts were masked. All ASF meals have the highest NIEI$_{\text{meal}}$ values, meaning they have highest environmental impacts and lower comparative nutritive values. A notable exception is the mycoprotein meal, an NFF produced with higher environmental impacts and scoring higher in NF$_{\text{meal}}$. Yet, the NIEI$_{\text{meal}}$ value for the mycoprotein meal was within the range of the other NFFs and less than all the ASF meals. The NIEI$_{\text{meal}}$ value accounts for the fact that mycoprotein is a nutrient dense food ingredient, placing it more in the comparable range of the other, less environmentally impactful, less nutritionally dense NFF and PBPR alternative meals. The NF$_{\text{meal}}$ score gives equal weight to the environmental impacts and a limited number of nutrients, where the nutrition as a functional unit in the NIEI$_{\text{meal}}$ value accounts for the fact that foods provide nutrition as primary function, basing relative environmental impacts on the nutrient content.

When all the environmental impacts were separated to calculate an NIEI value per meal per impact (NIEI GWP$_{\text{meal}}$, NIEI WU$_{\text{meal}}$, NIEI LU$_{\text{meal}}$, NIEI FE$_{\text{meal}}$, NIEI ME$_{\text{meal}}$, NIEI TA$_{\text{meal}}$), the separate NIEI values showed a similar relationship with the NIEI$_{\text{meal}}$ value (Fig. 5). Thus, the collapse of the separate environmental impact NIEI values into one NIEI$_{\text{meal}}$ index yielded a reliable score; a score which made for a fairer comparison with the NF$_{\text{meal}}$ values as all environmental impacts and nutrient compositions were also collapsed into the averaged NF$_{\text{meal}}$ values (see Supplementary Table 9 and Table 10 for all nutrition, environment, and index values by meal and by food ingredient, respectively). Beef and fish meals were again notable exceptions overall and, in particular, when scarcity-weighted water use and freshwater eutrophication impacts were considered in terms of nutrient richness.

4. Discussion

4.1. Environmental impacts by meal

Certain NFFs have the potential to act as substitutes for ASF in sample meals with up to 88 % lower GWP, 83 % fewer scarcity-weighted water use impacts, 85 % less land use, 95 % less freshwater eutrophication, 78 % less marine eutrophication, and 92 % less terrestrial acidification

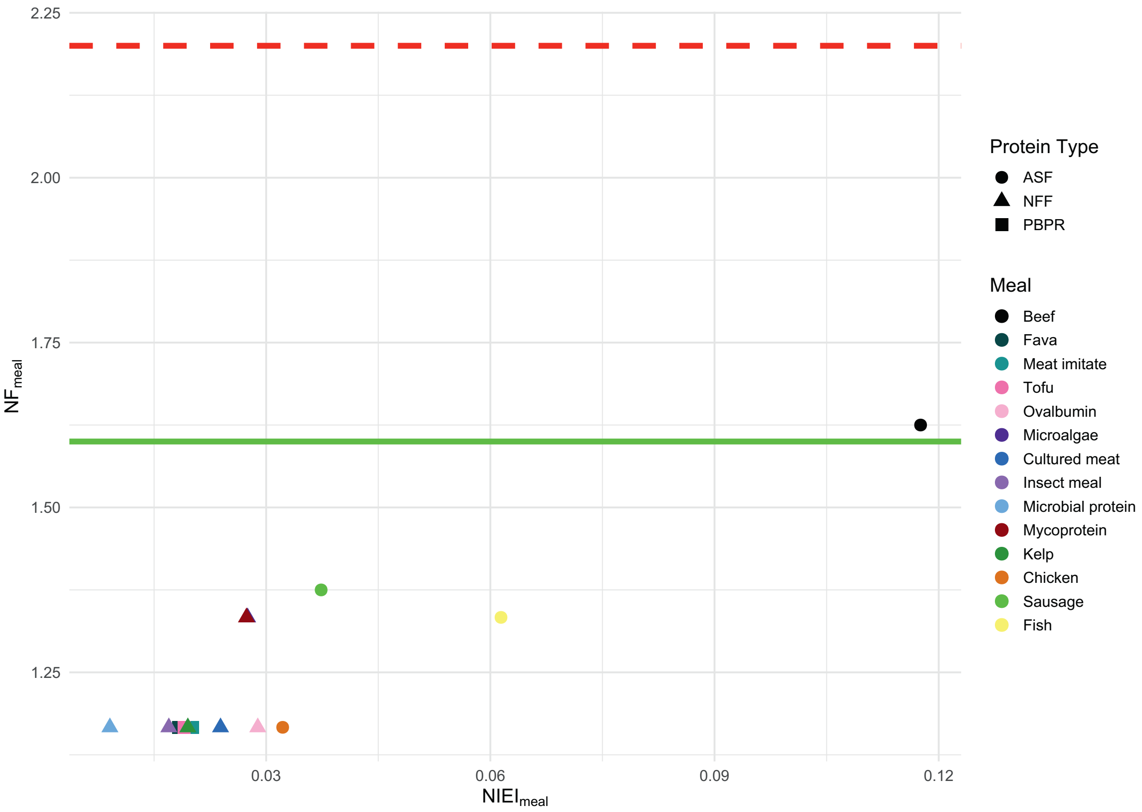


Fig. 4. Comparison of Nutrient Footprint and Nutritionally Invested Environmental Impact indices by meal. Nutrient Footprint (NF$_{\text{meal}}$) and its preset thresholds for high, medium, and low impact—below the green (solid) line at y = 1.6 is the low impact threshold, above the red (dashed) line at y = 2.6 is the high impact threshold, between low and high is the medium impact—compared with the Nutritionally Invested Environmental Impact index (NIEI$_{\text{meal}}$) by meal and protein type. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

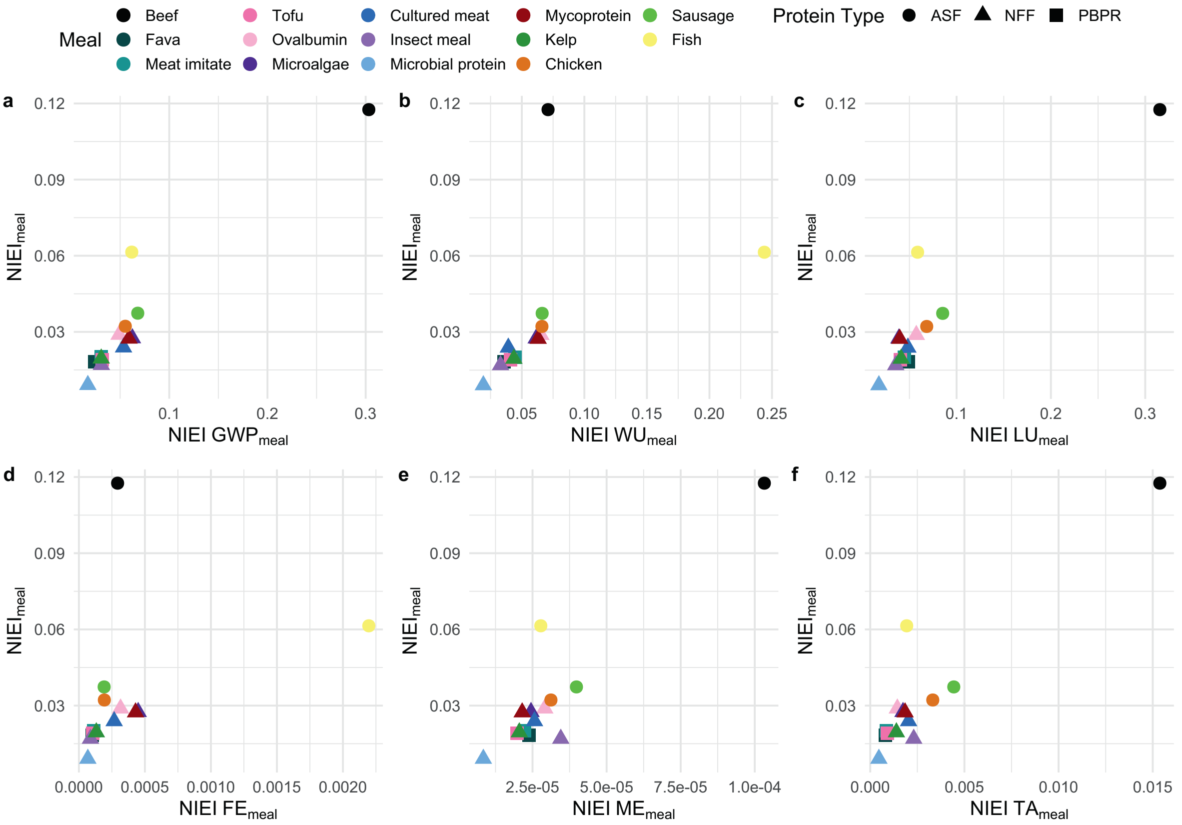


Fig. 5. Comparison of Nutritionally Invested Environmental Impact indices by separate and combined impacts. Nutritionally Invested Environmental Impact ($NIEI_{meal}$) by meal and protein type with separate NIEI values of a. Global Warming Potential (NIEI GWP_{meal}), b. scarcity-weighted water use (NIEI WU_{meal}), c. land use (NIEI LU_{meal}), d. freshwater eutrophication (NIEI FE_{meal}), e. marine eutrophication (NIEI ME_{meal}), and f. terrestrial acidification (NIEI TA_{meal}).

per meal. NFF meals have similar environmental impacts as previously modeled vegan/vegetarian lunches (Eustachio Colombo et al., 2020; Lukas et al., 2016). In general, meals with ASF protein patties ranked worse in terms of environmental impacts and $NIEI_{meal}$ score than NFF meals. Depending on the environmental impact, the mycoprotein, microalgae, and cultured meat meals ranked worse than some ASF. Though NFF meals generally performed better in terms of environmental impacts than the ASF meals, there was a large range of environmental impact discrepancies within the NFF meals protein type. NFF meals such as the insect meal, kelp, and microbial protein meals had lower average environmental impacts and ranked better in Agg $Impact_{meal}$ compared to other NFF meals such as the cultured meat, microalgae, and mycoprotein. These results indicate that the substitution of ASF with certain NFFs in meals would not have the same benefits in terms of environmental impact reduction as other NFFs.

Substituting ASFs—here, beef in particular—with PBPR alternatives reduced all environmental impacts. For example, the fava bean meal has over 75 % less GWP, scarcity-weighted water use impacts, land use, freshwater eutrophication, marine eutrophication, and terrestrial acidification than the beef meal. Our results confirm previous findings that vegan and vegetarian meals have consistently fewer environmental impacts than those containing ASF (Rivera et al., 2014; Saarinen et al., 2012). Total GWP in our meals with PBPR alternatives were similar to the environmental impacts of previously optimized lunch meals and offer similar relative nutritional intake for adult meals per day (Eustachio Colombo et al., 2020). Since no previous studies have examined the impacts and potential of changing individual meals by replacing ASFs with NFFs, our results may aid in understanding the substitutability of NFFs in meals (e.g., microbial protein patties for beef patties) when consumers make selections in restaurants, cafés, and stores.

Certain tradeoffs were revealed when all six environmental impacts were compared. Though ASF meals generally had higher environmental impacts and PBPR alternative meals fewer environmental impacts regardless of impact, individually or aggregated, there were large differences amongst the impacts within certain NFF meals. For example, the insect meal had low relative GWP, scarcity-weighted water use, land use, and freshwater eutrophication impacts, and ranked 3rd in Agg $Impact_{meal}$, but its marine eutrophication value was second to last, only performing better than the beef meal. The microalgae also ranked 12th in GWP, scarcity-weighted water use, and freshwater eutrophication impacts and 11th in aggregated environmental impacts but ranked 6th in land use. Such tradeoffs reveal that not all environmental impacts are correlated amongst each other, suggesting that substitution of ASFs with certian NFFs would not yield consistent reductions in environmental impact across all impact categories assessed. Some production processes may have higher GWP and lower land use, or low GWP and higher eutrophication and acidification potentials. There are important distinctions amongst foods which may consume more energy but less land and water, or vice versa. As more environmental impacts are considered in future comparative assessments, more information about the nuanced differences amongst environmental impacts may be revealed.

4.2. Nutrient Footprint

Our results show that PBPR, most NFF and ASF meals are similar in NF_{meal} to vegan and vegetarian meals in previous studies (e.g., mixed vegetable salad, veggie lasagna, vegan chili, potato pancakes) (Lukas et al., 2016). Yet, even the meal with the highest NF_{meal}, beef, was in the medium environmental impact range and had similar NF_{meal} scores as potato pancake and fish meals (Lukas et al., 2016). However, our meals were designed to have balanced nutrition and based on a meal recipe from an already low-GHGE optimized meal, including all ASF meals, so the NF_{meal} values cannot be realistically compared to Lukas et al.'s (2016). As Lukas et al. (2016) claim, the Carbon Footprint and Water Use Footprint capture abiotic resource use and the Land Use Footprint captures biotic resource use, we thus did not use their Material Footprint for our calculations since the other three footprints overlap significantly (Lukas et al., 2016). Instead, we adapted Lukas et al.'s (2016) methods with the addition of freshwater eutrophication, marine eutrophication, and terrestrial acidification to the NF_{meal} calculation. Given the wide range of differences amongst the environmental impacts within certain meals, the NFF meals in particular, it is likely that the inclusion of the three additional environmental impacts into the averaged NF_{envi} index masked any large variation and thus moderated the final NF_{meal} values. For example, the beef and fish meals had high environmental impact footprints for some impacts but medium NF_{envi} subtotals, which masked those categories with high impacts in the final NF_{meal} values.

Focusing only on four nutrients of interest in the NF_{health} does not show the complete nutritional value of NFFs in meals when compared to ASF and PBPR alternatives. Moreover, the fact that all meals were nutritionally balanced heavily influenced the low NF_{health} subtotals and overall low NF_{meal} values for all meals. The amino acid content of all but one essential amino acid in all meals was above recommended daily intakes, and NFFs may be subsequently engineered to provide a complete array of essential nutrients (e.g., amino acids, fatty acids such as Omega-3, calcium, and vitamin B12) (de Boer and Aiking, 2021; Parodi et al., 2018). The NF method also gives equal weight to the nutrition and environmental impacts, which means that a healthy meal with high impacts—such as our mycoprotein or fish meals—could still result in a low to moderate NF_{meal} score.

4.3. Nutritionally Invested Environmental Impacts

The Nutritionally Invested Environmental Impact score ($NIEI_{meal}$) is an index which gives the ratio of the standardized, averaged environmental impacts to the Nutrient Rich Food index (NRF24.4). Comparing meals in terms of the $NIEI_{meal}$, NFFs and PBPR meals had consistently lower ratios than ASF meals, meaning they have fewer environmental impacts and higher nutrient richness. Overall, ASF meals had the highest $NIEI_{meal}$ ratios, or the highest environmental impacts considering the nutrient richness. Our results were similar to previous findings when the $NIEI_{meal}$ values of individual ASF and PBPR food products were compared (Green et al., 2021). The beef meal had relatively high environmental impacts with low to moderate nutrient richness scores, as has been shown also in previous studies both in terms of scarcity-weighted water use and land use (Green et al., 2021) and in terms of GWP (Saarinen et al., 2017; van Dooren et al., 2017). When ranked by environmental impacts per meal, ASF meals performed poorly, though better than some NFFs, especially the mycoprotein, microbial protein, and cultured meat meals individual impacts and Agg $Impact_{meal}$. Yet, when considering nutrient richness as a functional unit, ASFs were ranked as the four worst meals in terms of the $NIEI_{meal}$ value. Thus, when nutrition is seen as a function, the PBPR and NFFs meals have low environmental impacts in terms of their nutrient richness, where ASF meals—beef and fish, in particular—showed higher environmental impacts even given their relatively high nutrient richness. Additionally, the relationship amongst the $NIEI_{meal}$ value and the respective NIEI values for the six impacts reveals that taking nutrition into consideration balances some of the tradeoffs amongst the direct environmental impacts.

4.4. Comparing nLCA indices

When comparing the nLCA indices (NF_{meal} and $NIEI_{meal}$), we found that the PBPR alternatives showed agreement between the indices, but the ASF and certain NFF meals were not always aligned. The NF_{meal} value yields information about how the meals compare when the nutritional and environmental subtotals are equally considered and averaged. The NF method also collapses all environmental impacts into one value, so even if one meal is higher in one environmental impact category, it may be balanced by the low environmental impact in another category. Similarly, some ingredients in the meal might make up for the high environmental impact of the protein source in the NF_{meal} (e.g., fiber in the vegetables). Thus, the individual differences amongst different food ingredients were completely masked in the NF_{meal} values. This phenomenon is evidenced in our results of the fish meal with high scarcity-weighted water use and freshwater eutrophication impacts but low land use, GWP and terrestrial acidification impacts, as well as having a relatively healthy nutritional profile. Similarly, the NF_{meal} values do not reflect the higher environmental impacts of the beef meal overall.

On the other hand, the NIEI method, taking 24 recommended and 4 nutrients to limit into account is more comprehensive than the NF method and other NRF scoring methods (Hallström et al., 2018; Sonesson et al., 2019). Thus, the $NIEI_{meal}$ value gives a metric for how environmentally impactful a meal is in relation to the nutrient richness of that meal. Indeed, previous studies which apply similar NIEI methods as an nLCA metric also find that considering nutrition as a function allows for avoiding the overly reductive comparisons on simple mass or continuous nutrient variables (Saarinen et al., 2017; Sonesson et al., 2019; Weidema and Stylianou, 2020). It is recommended to be comprehensive, but parsimonious when applying NRF indices. It is better to include both positive (i.e., qualifying) and limiting (i.e., disqualifying) nutrients in the nutrient richness scores (Drewnowski and Fulgoni, 2014). Previous studies validating NRF scores indicated that including more than nine or ten positive nutrients allows for little additional benefit for measuring diet quality (Fulgoni et al., 2009). Additionally, capping of nutrients at 100 % of recommendations was not used in this study since it has been recommended only at the diet level of analysis (Hallström et al., 2018). Yet, the implications of not capping nutrients in the $NRF24.4_{meal}$ score might mean that excessive values for single nutrients may disproportionately influence the final score, compensating for low intakes of other qualifying or high intakes of disqualifying nutrients. Thus, careful analysis of individual nutrient intakes is also required for more nuanced comparison of NRF scores. Such NRF scores are also dependent on dietary context (e.g., which other foods are eaten affecting bioavailability) (Hallström et al., 2018; Sonesson et al., 2019). Thus, the food composition of rest of the diet outside of a single meal could affect overall diet nutrient richness or bioavailability and may need to be included in future research.

Within itself, the NIEI method showed the same general trend in terms of single environmental impacts per meal and their relationship to the overall $NIEI_{meal}$. There is a strong positive correlation with all individual environmental impact NIEI values for all PBPR and NFF meals when compared to the overall $NIEI_{meal}$ value. Yet, NIEI WU_{meal} and NIEI FE_{meal} values for fish and beef do not show the same relationship as the NIEI GWP_{meal}, NIEI LU_{meal}, NIEI NE_{meal}, and NIEI TA_{meal} when all are plotted against the overall $NIEI_{meal}$ value. This means that the scarcity-weighted water use impacts, freshwater eutrophication, and GWP of the fish and beef meals are outliers in the overall trend. Such differences in environmental impacts are masked in the overall $NIEI_{meal}$ value. Thus, the NIEI method may be more comprehensive when disentangling the nutritional complexities of the meals but needs to be critically evaluated when environmental impacts are aggregated. Additionally, nutrient dense foods, such as mycoprotein, warrant more nuanced assessment methods as the mycoprotein meal was consistently high in environmental impacts but was the 8th best overall in $NIEI_{meal}$. Integration of health and environmental aspects of meals in single scores are prerequisite tools for seeking sustainability in food systems (Hallström et al., 2018).

The usefulness of the results of nLCA will depend on several aspects which must be considered when applying different nLCA methods in different situations. It is imperative to consider the purpose of the results; when ranking meals in terms of environmental impacts and nutrients, the combination of the two components into one score is needed. Conversely, when optimizing or investigating the direct environmental impacts and nutrient content of a diet or meal, the synthesis of the environmental impact and nutrient components is not recommended since information is lost in indexing the values (Hallström et al., 2018). Combining all environmental impacts into one synthesis environmental impact score has not received robust and validated attention, but such indices are being developed for food product LCA and should be investigated further (de Bauw et al., 2021; Tukker et al., 2011).

4.5. Other NFF considerations

Our findings suggest that meals could be more land, water, and carbon efficient with fewer eutrophication and acidification impacts if current ASF meals are adjusted to include PBPR alternatives or certain NFFs. NFFs can play a role in the sustainable protein landscape and present options which meet the requirements of nutritious protein alternatives. The fact that most NFF and PBPR alternative meals have consistently low nLCA values indicates that these products have the best balance of tradeoffs amongst nutritional content and lowest environmental impact given current data.

The limits of cultural acceptability and consumer adoption of NFFs as viable ingredients in meals must be considered. Consumers appear to be more amenable to adopting PBPR alternatives than cultured meat and insects (Onwezen et al., 2021). Generally, influenced by taste, health, food neophobia/disgust, and social norms, consumers are most concerned with perceived naturalness and familiarity of NFFs in Europe (Siegrist and Hartmann, 2020). Thus, substitution of ASFs with NFFs in sustainable future diets and meals warrants further, more diverse forms of investigation. Given the importance of organoleptic properties of food and the need for diversity in the diet, more research is needed to understand such properties as taste and texture in NFFs (Schmidt and Mouritsen, 2020; Willett et al., 2019). Moreover, certain ASFs retain important in cultural and social values and may thus be unrealistic to completely remove from diets (Schmidt and Mouritsen, 2020). However, education and advertising which highlights health, social, and environmental benefits of NFFs, such as antioxidant/anti-inflammatory properties or climate 'risk-resilient' protein production methods without jeopardizing animal welfare, may increase acceptance, though adoption is still largely dependent on taste and price (Bryant and Barnett, 2020; Tzachor et al., 2021).

4.6. Limitations and future directions

The NFFs compared in this study were chosen based on availability of LCA data on NFFs. Other potential challenges related to the high energy demand for novel production processes must be considered when including NFFs in future meals (Järviö et al., 2021a; Järviö et al., 2021b; Kobayashi et al., 2022; Tuomisto et al., 2022). The technologies for NFF production are still under development. In particular, the LCA data for the cell-cultured foods included in this study are based on the relatively small-scale production processes. Therefore, technological development can improve the environmental efficiency of the NFF products in the future. We are also limited here by the available knowledge on nutritional and health aspects of NFFs; fortification possibilities, including vitamins D and B12, and consideration of the bioavailability of nutrients in NFFs are areas of relevance for future research.

More work is needed to fully understand the environmental impacts, cultural and ethical considerations, and economic affordability aspects of NFFs. Future research should discuss the scalability and viability of the future production of NFFs, validate meals constructed with such products, and expand nLCA indices applied to meals for clearer implementation in sustainable food systems transformation. Ideally, future research would involve more NFFs and investigate their use in other meals as well as potential consumer taste preference intervention studies with those meals. Further distinctions amongst the environmental impacts of the various ASF production systems (e.g., grass-fed/organic vs. conventional beef) could also reveal nuances in the impacts of the ASF meals and should be considered in future studies. We also do not include here emerging PBPR alternatives as ASF substitution products, which are becoming popular in vegan diets, such as processed meat imitation products.

Moreover, the challenge of assessing the overall sustainability of meals, which goes beyond nutritional and environmental impacts, cannot yet be concretely distilled into any one indexed value (Hallström et al., 2018). Although, these six environmental impact categories do not yield a complete analysis of the environmental sustainability of food production and consumption, they do provide a representative sample given that these are the most relevant environmental impact categories for food production (Campbell et al., 2017; Crippa et al., 2021; Hallström et al., 2022; Humpenöder et al., 2022; Pikaar et al., 2018; Poore and Nemecek, 2018; Sillman et al., 2020). Further work could apply a differential weighting of the environmental impacts as previous studies have done in aggregate environmental scores (Tukker et al., 2011). Further research would also need to consider possible tradeoffs amongst more environmental impact categories including biodiversity impacts and ecosystem services, incorporate the dynamics of different production systems, and develop such limited nutritional indices to be suitable for use in the context of LCA.

5. Conclusion

Our study is the first of its kind to compare environmental impacts and nLCA indices of meals including NFFs. We show that nutritious meals can be constructed with NFFs and have similar, or greater environmental impact reductions as meals with PBPR alternatives over ASF meals. Employing nLCA, over simply eLCA, has the added advantage of considering nutrition as the functional unit in assessing the sustainability of foods, nutrition being a primary, if not the main, purpose of producing and consuming food. Integration of production and consumption, environmental impacts, and nutrient content of foods is an imperative and practical step in any further transformation of diets, meals, and food production for sustainable food systems.

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Code availability

The code generated during and used during the current study are available from the public repository: https://version.helsinki.fi/rachel.mazac/nffs-meals.git.

CRediT authorship contribution statement

Rachel Mazac: Conceptualization, Formal analysis, Investigation, Project administration, Visualization, Writing – original draft. **Natasha Järviö:** Data curation, Validation, Writing – review & editing. **Hanna L. Tuomisto:** Conceptualization, Data curation, Validation, Funding acquisition, Supervision, Writing – review & editing.

Data availability

All data generated or analyzed during this study are included in this published article (and Supplementary Material file). Files can be found in the public repository: https://version.helsinki.fi/rachel.mazac/nffs-meals.git.

Declaration of competing interest

The authors declare no financial interests/personal relationships which may be considered as potential competing interests.

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