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Optimised diets for achieving One Health: A pilot study in the Rhine-Ruhr Metropolis in Germany

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ABSTRACT

Dietary changes are needed to align the global food systems with the planetary boundaries and contribute to Sustainable Development Goals. We employed a Life Cycle Assessment (LCA) framework, extended with indicators on human health and animal welfare, to assess 2020 food consumption data of a pilot sample collected through an online survey in the Rhine-Ruhr Metropolis (Germany). Feasible optimisation scenarios representing alternative sustainable choices towards overarching environmental, societal and policy goals were explored. Meat and meat products contributed most to overall environmental impacts (e.g., climate change, terrestrial acidification), and fish and seafood to animal welfare loss (e.g., animal lives lost, animal life years suffered). Sodium intake was the most contributing risk factor for life minutes lost. The combined optimisation scenario reduces 55% of greenhouse gas emissions, improves human health indicators by 25% and reduces animal welfare loss substantially (by 52-97%). This is possible with a shift towards flexitarian and vegetarian dietary scenarios. These optimisations deliver improvements across One Health dimensions with marginal changes in dietary scenarios and align with the sustainability goals of the EU Green Deal. Working with regional data can offer advantages in obtaining more realistic baseline dietary information to promote localised dietary shifts. While this research has limitations regarding sample representativeness, it can serve as a case study to encourage sustainable consumption in the Rhine-Ruhr region.

1. Introduction

Global food production and consumption are heading beyond safe planetary boundaries, and urgent transformations are necessary to ensure food security and climate change mitigation (Aiking and de Boer, 2020; Gerten et al., 2020). Food systems are increasingly altering ecosystems while causing unprecedented global health burden, including communicable and non-communicable diseases (NCDs) (Ridoutt et al., 2021; Talukder et al., 2022). The UN Food Summit emphasised the need for profound dietary changes for a sustainable future for better human, animal, and ecological health (UN, 2021; von Braun et al., 2023). Consequently, diets should shift towards more environmentally sound, healthy and ethical consumption patterns that respect planetary boundaries, acknowledging regional differences and socio-cultural values (Vanham et al., 2021).

The European Union's (EU) Green Deal aims to reduce greenhouse

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gas emissions (GHGE) by 55% in 2030 by transforming the EU food systems (European Commission, 2021). The EU's Farm to Fork Strategy targets both consumption and production, focusing on environmental and socioeconomic aspects (European Commission, 2020). While EU consumers are becoming more aware of sustainability issues, meat remains relatively cheap and widely available in the food basket (de Boer and Aiking, 2022). In Germany, Western diets high in animal-sourced foods intake predominate, with a total meat supply quantity of 78.9 kg/capita/yr. in 2020 (FAOSTAT, 2023; Helander et al., 2021). The Rhine-Ruhr Metropolis is a densely populated urban area in the federal state of North-Rhine-Westphalia (NRW), one of Germany's leading poultry and pig livestock producers (Deblitz et al., 2022). Nevertheless, concerns have been raised about agricultural sustainability, animal welfare labels, and nutrition (BMEL, 2020). Developing sustainable solutions and investigating various dimensions encompassing the transformation of urban food systems is important.

Life Cycle Assessment (LCA) is a widely used tool to assess the sustainability of food consumption, compare diets, and support the baseline for alternative scenarios (Heller et al., 2013). While LCA focuses primarily on environmental aspects, more comprehensive sustainability assessments warrant further investigation involving multiple societal dimensions (Nemecek et al., 2016). Progressively, more studies have explored other dimensions, including human health and animal welfare (Jolliet, 2022; Scherer et al., 2019). These indicators intersect the One Health (OH) approach, which combines the health of humans, animals and the environment as essential for transitioning towards more sustainable food systems (Angelos et al., 2017). Although studies scrutinise OH towards the classical approach, narrowing it down to the human-animal interface zoonotic transmission (Lebov et al., 2017), other studies emphasise an extended approach, incorporating environmental interactions, chronic diseases, mental health and wellbeing (Falkenberg et al., 2022; Schmiege et al., 2020).

Although One Health is recognised as having an important role in the sustainability of food consumption, recent studies using multidimensional LCAs still lack the animal health component (Gibin et al., 2022). A recent study integrates animal welfare and human health indicators into an extended LCA framework (Paris et al., 2022a). However, estimating human health impacts is challenging due to the lifetime dietary risk intake at the population level versus individual daily food intake (Paris et al., 2022b). The "Health Nutritional Index" (HENI) estimates the marginal human health burden attributed to food intake in a single score, facilitating the link between population-level health burden and daily food intake (Stylianou et al., 2021). A few studies applied HENI to assess the health implications of food consumption (Jolliet, 2022; Pink et al., 2022). However, the potential of HENI to assess diets from a multidimensional LCA perspective remains underutilised (Thoma et al., 2022). Moreover, animal welfare is often neglected in LCA, with few exceptions, despite the relevant public concern towards animal farm conditions (Bonnet et al., 2020). Animal welfare is a complex societal issue intrinsically interconnected with human well-being and the environment at different levels (Garcia, 2017). Beyond public and political appraisal, animal welfare moves consumer expectations to more ethical production systems, especially in Germany (BMEL, 2020).

Still, it remains challenging to influence consumer choices as consumption decisions are largely based on satiety, affordability and cultural values (Batlle-Bayer et al., 2020; Ridoutt, 2021). That is why some studies implement diet optimisation to assess the effects of dietary changes. Optimisation calculates optimal dietary scenarios fulfilling determined sustainability and nutritional criteria closest to actual dietary behaviour, thus being more feasible for individuals to adhere (Kramer et al., 2018; Tyszler et al., 2016). Optimising self-reported dietary practices captures more representative and realistic food choices, identifying minimal dietary changes to achieve sustainability goals, ideally at a sub-national level (Vieux et al., 2022).

The novelty of our study is optimising the sustainability of real diets in a pilot study conducted in a metropolitan region in Germany using an extended LCA framework combining environmental, human health and animal welfare dimensions. Food consumption data was collected in 2020 from a pilot sample via online questionnaires disseminated among inhabitants in the Rhine-Ruhr Metropolis during the first year of the COVID-19 pandemic. Three dietary patterns were observed: Prudent, Western type 1 and Western type 2. Four optimisation scenarios representing alternative sustainable choices towards overarching environmental, societal and policy goals were explored to optimise baseline dietary patterns: i) reducing GHGE by 55%, ii) zero animal welfare loss, iii) improving health indicators by 25%, and iv) combined scenario. Overall, we aim to identify more effective scenarios in reducing impacts from food consumption towards more sustainable dietary choices encompassing the three dimensions of One Health, considering the trade-offs among these dimensions.

2. Methods

2.1. Study design

The study developed an online data collection method adapted to the pandemic between June 2020 and January 2021 to collect data on food consumption for a pilot study aiming to optimise diets to achieve "One Health". Participant recruitment was done extensively via social media networks, community digital networks, and postcards with QR codes advertised in commercial and residential areas within the Rhine-Ruhr Metropolis. This metropolitan region is located in NRW, composed of 21 cities ("*kreisfreien Städte*") and 15 districts ("*Kreise*") with approximately 14 million inhabitants (Destatis, 2022a; IKM, 2022). The area is one of the largest conurbations in Europe, economically relevant as an industrial pole and innovation hub and has recently progressed to become the greenest metropolitan region in Germany (Goess et al., 2016).

Participants of 18 years of age or older completed a general survey on demographics and a validated and cost-effective food frequency questionnaire EPIC II (FFQ) (Nöthlings et al., 2007), developed by the German Institute of Human Nutrition Potsdam-Rehbrücke (Harttig, 2021). Participants under 18 were withdrawn from the study. A written informed consent was provided digitally by recruitment. The Research Ethics Committee, Center for Development Research at the University of Bonn approved ethical clearance.

A total of 206 participants registered for the survey after six months of active survey dissemination. From them, 189 participants ($N = 189$) filled out the FFQ, and 183 completed the socio-demographic survey. Invalid questionnaires were treated as missing cases ($n = 11$), and 6 participants who were not residents of the Rhine-Ruhr Metropolis were excluded. Although the sample is small, it has a 6.69% margin of error within a 95% confidence interval with an effect size of 0.995, estimated by power for one-way ANOVA, F-test for group effect with group variance 0.1 to 1.0 ($\alpha = 0.05$), including male ($n = 46$), female ($n = 140$), total population size ($N = 206$) and optimal sample size for adult population in NRW (ideally 316). The study population is majority female (76.9%), German nationality (89%), 50% ranging from 32 to 56 years old, possessing graduation or higher level of education (63.4%), with an average monthly income of Int$ 5956 ± 370 (see **Table S1** in the **Supplementary Information (SI)).**

2.2. Life cycle assessment: goal and scope

This LCA study follows the framework proposed by Paris et al. (2022a), based on the ISO14040/44:2006 (ISO, 2006a, 2006b). The system boundaries included crop and animal production, transport of raw materials, processing, packaging production, distribution, retail, consumption, transportation between sub-stages, food losses and waste and food packaging disposal (**Fig. S1** in **SI**). Waste management and disposal were excluded. Economic allocation was assumed when different co-products were obtained using the same process (European

Commission, 2018). Except for dairy, which follows the International Dairy Federation guide that applies physical allocation among meat and feed and dairy co-products (skimmed milk powder, cream and milk fat derivates) (Broekema et al., 2019; International Dairy Federation, 2016). Cut-off criteria were applied for a few co-products (citrus pulp, brewer grain, animal manure, and nutshells) due to their low economic value (Broekema et al., 2019). Emissions from land-use changes (LUC) were not covered, as these require modelling techniques to simulate future land transformation caused by future food demand changes.

2.3. Life cycle inventory (LCI)

2.3.1. Food data

The FFQ estimates daily food and nutrient intake over the last 12 months, categorised into 19 major food groups, including diversified food items and beverages. The quantities of specific food items within respective food categories were estimated using food frequencies. The LCI food data was based on the EFSA food and nutrient database (EFSA, 2018a, 2019a). The mapping of food items consisted of reallocating them into different food categories, renaming them, allocating them into the most representative food item within the group, or reallocating them to proxies. Due to their intake representativeness, 13 food items were added: avocado, broccoli, cherries, decaffeinated coffee, dried fruits, figs, game meat, grapes, olives, rabbit meat, soymilk, tofu and zucchini. For these, LCI was complemented with the EFSA food composition data (EFSA, 2019a), nutrient intake in g/day from the FFQ and other sources (RIVM, 2021) — further details on assumptions in **Table S2** in **SI**.

Factor analysis was conducted in IBM SPSS v.28.0 (IBM Corp, 2021) over the inter-correlation between food intake, food items and categories to identify patterns in food consumption. The dietary patterns were defined by clustering average group linkages and grouping together the cases within specified patterns. Three distinct dietary patterns were observed within the sample $N = 189$: (a) **Prudent (PRU)** ($n =$ 73), (b) **Western-type 1 (WT1)** ($n = 60$), and (c) **Western-type 2 (WT2)** ($n = 56$) (**Table S3** in **SI**). PRU (1897 kcal) has a high intake of fruits, vegetables, and animal protein substitutes, with low animal protein intake. WT1 (1867 kcal) has a high intake of meat, grains, eggs and alcoholic beverages. WT2 (2240 kcal) is high in dairy products, fish, eggs, grains, and processed snacks. The average daily intake per person in this population segment was the functional unit used to compare the observed diets, estimated at 3.44 kg, 2.73 kg, and 3.57 kg of food for PRU, WT1, and WT2, respectively.

2.3.2. Inventory data

The environmental background data was available in the software Optimeal® (Broekema et al., 2019), which aggregates impact values and nutrients per 100 g of food product from *farm-to-fork*. This LCI used SimaPro, based on the Agri-footprint 4.0 methodology, and additional data sources in agricultural production, transport, and processing (Durlinger et al., 2017a, 2017b). Energy and water use followed the Product Environmental Footprint (PEF) Guidance 6.3 (European Commission, 2018). Agricultural products' origin considered import mix and underlying transport distances for raw materials, based on FAOSTAT agri-food trade data and additional statistics (Broekema et al., 2019; FAOSTAT, 2013). The transport of raw materials between each substage included the different transport modality features (road, rail, water, and air) (Broekema et al., 2019). Packaging production was based on the Ecoinvent 3 (Wernet et al., 2016) and the ELCD databases (JCR-IES, 2012). The distribution and the retail were modelled as per the PEF Guidance (European Commission, 2018), considering the energy use during the storage time and food losses at the retailer. The consumption level considered energy use for several cooking methods, raw-to-cooked ratio, and food losses (European Commission, 2018). The disposal of packaging material was modelled in the European context using the Ecoinvent database 3.4 (Wernet et al., 2016). Impact values per 100 g of the extra 13 food items were added using data from existing literature. LCI data sources and assumptions in estimating environmental impact categories for food items are in **Table S5** in **SI**.

2.4. Life cycle impact assessment (LCIA)

The environmental dimension was assessed with eight environmental impact categories at the midpoint level, according to the ReCiPe Midpoint (H) 2016 characterisation method, in line with the recommendations of the Product Environmental Footprint (PEF) (European Commission, 2018; Huijbregts et al., 2017). The ReCiPe 2016 Method is well documented in the context of Europe and a consistent framework for assessing impacts from the FU: food consumption in a sample group in the Rhine Ruhr Metropolis.

The eight selected environmental indicators are: 1) fine particulate matter formation [kg $PM_{2.5}$ eq], measured by the concentration of particulate matter by emissions of NH_3, NO_x, SO_2 and $PM_{2.5}$ to the air; 2) fossil resource scarcity [kg oil eq], measured as the ratio between fossil resource heating and crude oil energy; 3) freshwater eutrophication [kg P eq], measured as phosphorous emissions to freshwater; 4) global warming [kg CO_2 eq], measured as the radiative force of increasing of greenhouse gases emissions to the atmosphere; 5) land use [m^2a crop eq], measured as land occupation of annual crop equivalent; 6) marine eutrophication [kg N eq], measured as nutrient matter enrichment originated from N compounds; 7) terrestrial acidification [kg SO_2 eq], measured as acidification of soils due to SO_2 deposition and emissions from the atmosphere, and 8) water consumption [m^3] measured as m^3 water consumed (Ferreira et al., 2011; Huijbregts et al., 2017; Roy et al., 2014).

Three animal welfare indicators represented the animal health dimension: "Animal Life Years Suffered [ALYS]", "loss of Animal Lives [AL]", and "loss of Morally Adjusted Animal Lives" [MAL], following the proposed framework by Scherer et al. (2018). ALYS represents the loss of quality of life attributed to farming conditions considering German minimum requirements, including improved standards. AL captures premature death and suffering through slaughtering within the EU context. MAL measures the degree of animal awareness of experiencing negative sensations based on neural development. Impact values, assumptions and equations for calculating indicators and LCI sources for cattle (beef and milk), calf, pig, chicken (broiler and laying hens), turkey, salmon and trout, and several processed foods containing animal ingredients were retrieved from our previous studies (Paris et al., 2022a). This study calculated new impact values per 100 g for rabbit meat, red deer (as game meat), sheep (as lamb meat), and shrimp. The quality of life of rabbit meat and shrimp was calculated based on the stocking density. For sheep meat, we used the days of pasture/year. Wild deer hunting practices were assumed to estimate the impact of game meat on animal welfare. Animal welfare impacts from food items containing animal products (e.g., custard, dressing, mayonnaise, and pork liver) were calculated considering the quantities of the ingredients for each preparation/processing method. Detailed information on the calculations, criteria, assumptions, and data sources are found in **S4** and **Table S6** in **SI**.

2.5. Dietary risk factors and HENI

Human health impact is quantified as a marginal health burden using the "Health Nutritional Index" (HENI) proposed by Stylianou et al. (2021). HENI measures the combined health benefit of all dietary risk, scaled to minutes of healthy life gained, considering lifetime chronic intake. HENI is calculated using Dietary Risk Factors (DRFs, in $\mu DALYs/_{g\ risk\ component}$) that express the burden of disease per gram of intake amount of each of 15 dietary risks. Information on dose-response of all the 15 dietary risks and the corresponding diseases was obtained from the Global Burden of Disease study 2019 (GBD 2019) database, as well as the disease burden and mean dietary intakes at the country-level (Germany) (Global Burden of Disease Collaborative Network, 2020).

All DRFs were standardised to the population of Germany according to age, gender and population number using data from the last census (2011) (Destatis, 2022a). Once GBD does not provide the intake variance, we assumed a conservative coefficient of variation of 70%, based on the mean coefficient of variation observed in the US population using the National Health and Nutrition Examination Survey (NHANES) 2011–2016. However, we performed sensitivity analysis by varying DRFs using a wider range of coefficient of variation from 35% to 140% (**Table S9** in **SI**).

HENI was calculated for all 110 food items by 100 g. All NCDs associated with DRFs, as well as dietary risk definition and threshold levels based on the GBD 2019 study (Murray et al., 2020), can be found in **Table S7 in SI.** Nutrients and food group intake was used as LCI input for HENI calculations (e.g., calcium, sodium, omega-3 and trans-fatty-acid, vegetables, fruit, legumes, processed meat intake) based on the EFSA food composition table (EFSA, 2018a). This food composition table comprises >60 nutrients (macro and micronutrients) for over 2500 products in several European countries (Broekema et al., 2019). HENI (minutes of healthy life gained/person/day) was calculated using Eq. (1). It is the result of the multiplication of the constant *-0.53 min* by the cumulative standardised *DRF* per gram of dietary risk component ***r*** (in $\mu DALYs/g_{risk\ component}$, e.g. $\mu DALYs/g_{sodium}$ or $\mu DALYs/g_{legumes}$) and the amount of dietary risk component r per person per day (d_r, in $g_{risk\ component}$/person/d) above or below the healthy threshold levels by each food item.

$$HENI_{food\ item} = -0.53 \sum_r DRF_{r,DALY} \times d_{r,food\ item}\ 1\ \mu DALY = 1\ year\ of\ healthy\ life\ lost \times 365\ (days\ per\ year) \times 24\ (hours\ per\ day) \times 60\ (minutes\ per\ hour) \times 10^{-6} = -0.53\ minutes$$

Sodium used additional modifiers mediated by systolic blood pressure, dependent on ethnic group and hypertension incidence in the population (Stylianou et al., 2021). We considered both direct and mediated effects (via increased systolic blood pressure). The prevalence of hypertension in Germany (31.6%) was based on epidemiological studies (Neuhauser et al., 2015). The vulnerable population to hypertension was taken as the percentage of African descendants in the population (0.65%), assumed to be proportional to the number of foreigners in Germany from African countries (Destatis, 2022b). Details on calculating DRFs can be found in **S5** in **SI**.

2.6. Diet optimisation

Quadratic optimisation was applied to the three observed diets through 100-run Monte Carlo simulations in Optimeal® to evaluate differences in trade-offs on the shifts of optimised properties among optimisation strategies while satisfying several nutritional constraints. Quadratic programming increases the penalties when changing the grams of each food item, producing shifts on a larger range of food items but less amount in grams of each modified food item. This is meant to capture realistic changes in food consumption to be adopted by consumers, as they are not significantly different from the observed food basket (Broekema et al., 2019; te Pas et al., 2021). The algorithm followed the approach described by te Pas et al. (2021) (**Eq. 2**), where i represents each food item of all 110 food items, x_i is the total quantity in grams of each food item in the current diet, and x_i^*, quantity in grams of each food item of the optimised diet.

$$deviation = \sum_{i=1}^{110} \left(x_i^* - x_i\right)^2$$

Nutrient data comprised 60 nutrients (macro and micronutrients) using the European Food Composition Database (EFSA, 2018a). Nutritional constraints were applied using upper and lower nutrient values for every nutrient according to EFSA average nutrient requirements (EFSA, 2018b, 2019b). The only exception was vitamin D and B12, whose lower values were not considered due to difficulties finding feasible outcomes from Monte Carlo simulations. Linear programming was also conducted as a sensitivity analysis (see **SI, part S6**). The following arbitrary interventions were defined on top as scenario analysis to represent potential sustainability improvements in line with EU policies and societal demands:

(a) **55% GHGE reductions (55% GHGE):** a hypothetical scenario to reduce GHGE by 55% of each diet aligned to the EU 2030 climate targets as part of the EU's Green Deal.
(b) **Zero animal welfare loss (Zero AWL)**: a scenario to reduce animal suffering by eliminating all animal-based products from the diet. Minimum amounts of fruit, vegetables, whole grains, water, nuts and seeds, legumes and vegetable protein were kept equal to the observed diets to avoid decreasing the intake of these food items and remaining similar to the original diets.
(c) **25% improvement in health indicators (25% Health):** this scenario encourages or discourages the intake of certain food items, groups, or nutrients. It is characterised by an increase of 25% in beneficial DRFs and a decrease of 25% in detrimental DRFs, representing improved human health through modified dietary intake.
(d) **Combined scenario (Combined):** this scenario combines an increase of 25% in human health benefits and a reduction of 55% of GHGE in diets and evaluates the animal welfare reduction outcomes without removing animal products from the optimised scenario.

3. Results

3.1. Cross-comparison of observed diets using the OH approach

Results show WT2 has the highest mean values in almost all environmental and animal welfare indicators (Fig. 1) compared to WT1 and PRU (see Fig. 1). The exceptions are water consumption (Fig. 1k), greater in PRU due to a larger share of plant-based foods, e.g., legumes, nuts and oilseeds (with nuts having a higher share of the impact), vegetables and vegetable products, fruits and fruit products, and non-alcoholic beverages; and morally adjusted animal lives (MAL) (Fig. 1c), pronounced in WT1, due to a higher meat intake.

Among the food categories, meat and meat products make the greatest contribution to overall environmental impacts in all diets, ranging from 22% in fossil resource scarcity (Fig. 1e) to 47% in terrestrial acidification (Fig. 1j). In water consumption (Fig. 1k), higher in PRU, around 47% of the impact are due to fruit and fruit products, non-alcoholic beverages, vegetable and vegetable products, and legumes, nuts and oilseeds altogether. The most contributing individual food items to environmental impacts in all diets are beef, sausages, pork/piglet meat, cheese and pastries.

Fish and seafood make the greatest contribution to animal welfare loss in all diets, ranging from (65 to 69%) in animal lives lost (AL) (Fig. 1a) and, on average, 36% in animal life years suffered (ALYS) (Fig. 1b). Because smaller animals take a higher number of animals affected than larger animals to produce the same amount of food in kilogram. Meat and meat products are the main contributors to MAL in WT1 (79%), in PRU (63%), and WT2 (58%) (Fig. 1c). Milk and dairy products also showed a substantial contribution to ALYS in PRU (28%) and WT2 (24%). Shrimp, chicken, turkey, fish fingers, and salmon are the most impacting food items to animal welfare loss.

HENI captures minutes of healthy life gained through NCDs across the observed diets. WT1 and WT2 caused more life minutes lost than PRU (Fig. 1l). Cardiovascular diseases account for most minutes of life lost due to NCDs (Fig. 2a), especially in PRU. Nearly 7 min of healthy life are lost in hypertensive heart disease (HHD), and 3 min, in ischemic stroke (ISTR) in PRU, attributed to high sodium intake. Sodium intake causes a

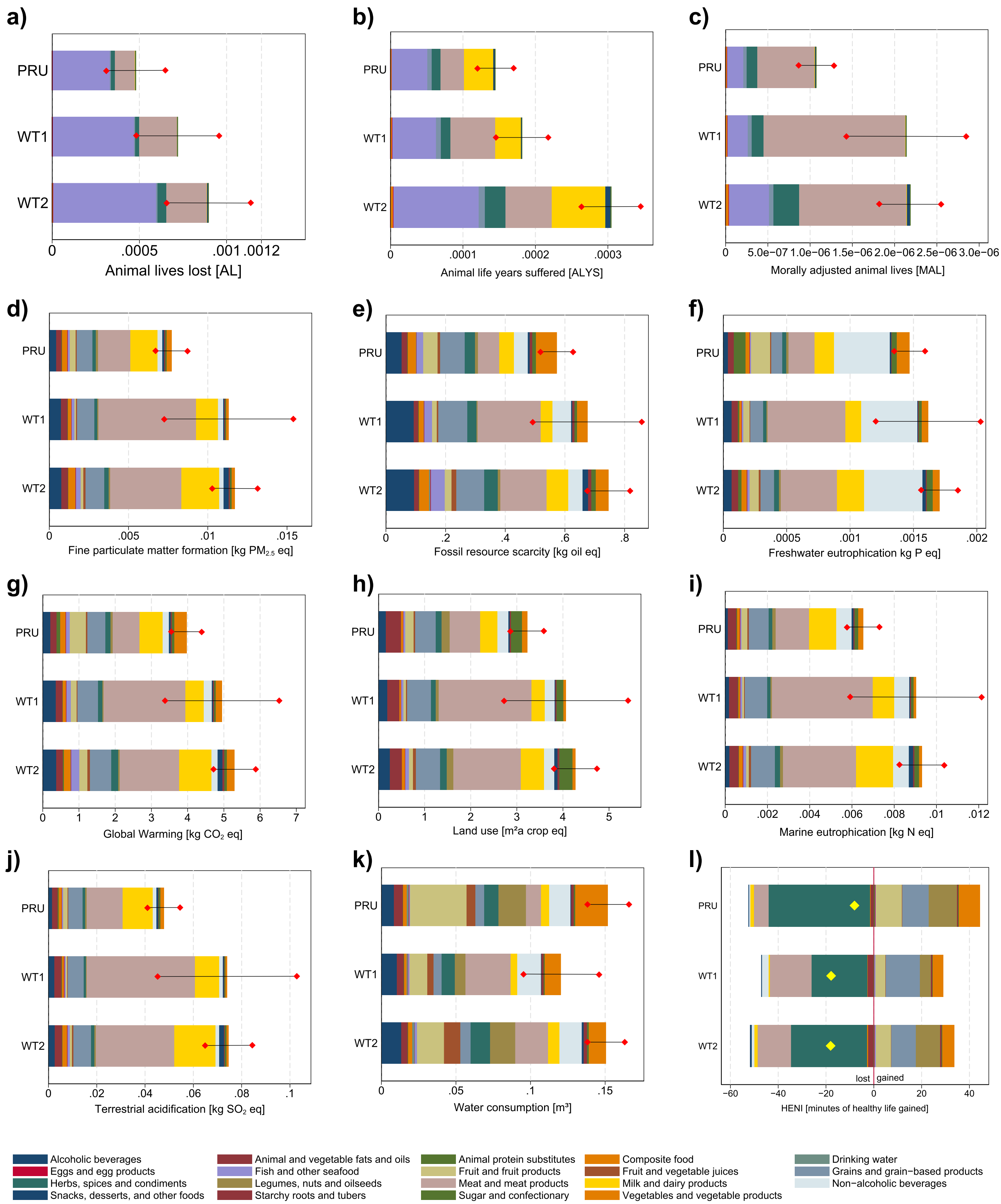

Fig. 1. Impacts by food category per diet and day. Red diamonds represent 95% confidence interval error bars of the average intake considering the number of observations. Yellow diamonds are HENI net values. Stack bars represent the sum of impacts per food category. Bar colours follow the order presented in the legend. Note: PRU: Prudent; WT1: Western-type 1; WT2: Western-type 2; HENI: Health Nutritional Index. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

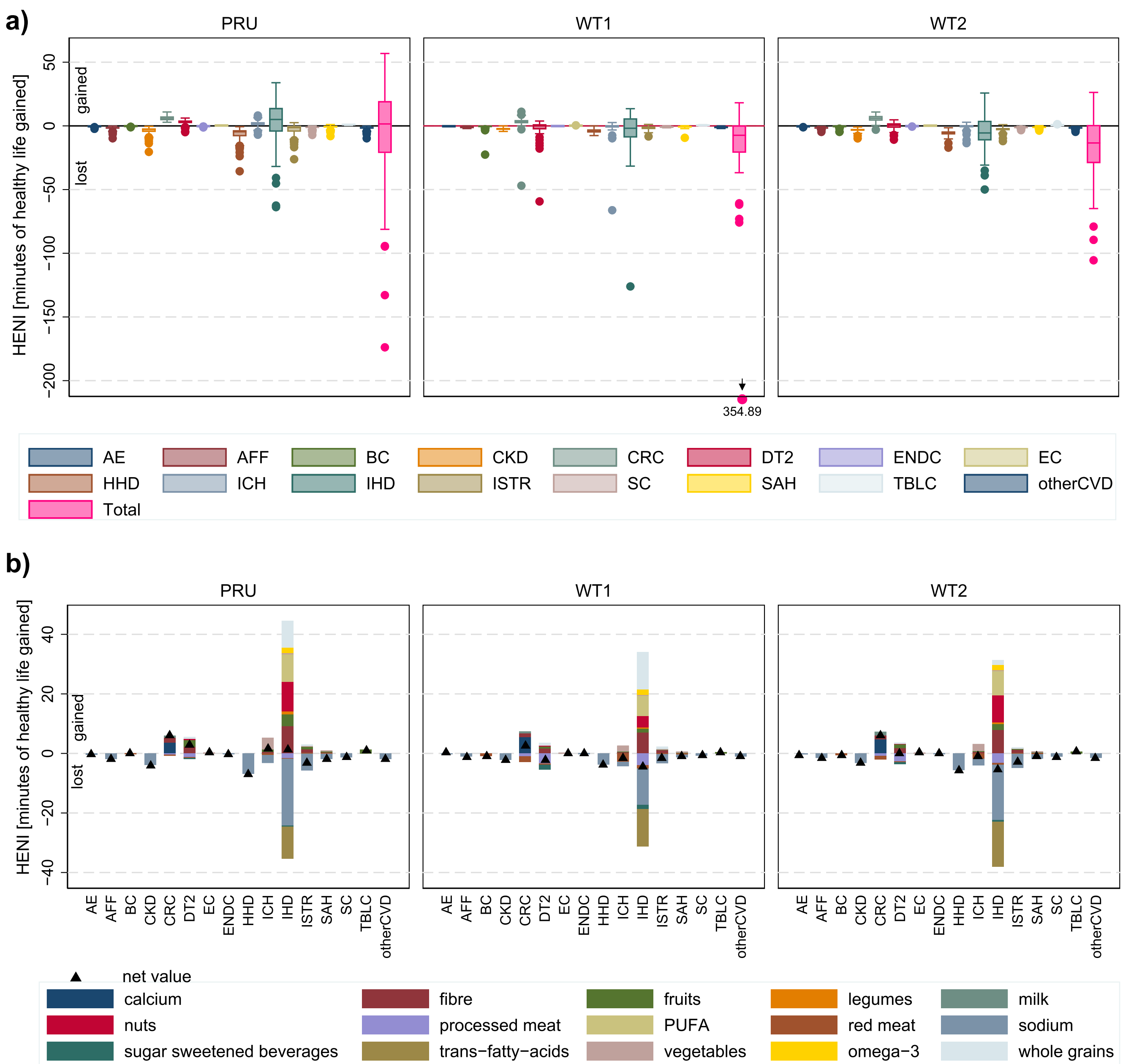

Fig. 2. Health Nutrition Index (HENI) for each diet by non-communicable diseases (a) by dietary risk factors attributed to non-communicable disease (b). (a) Boxplots represent Q1: lower quartile, Q2: median, Q3: upper quartile, error bars are upper and lower adjacent values, and markers are outside values at 95% confidence intervals. (b) Stacked bars represent the sum of HENI by dietary risk factors, and black triangles represent mean values. Note: PRU: Prudent; WT1: Western-type 1; WT2: Western-type 2; AE: Aortic aneurysm; AFF: Atrial fibrillation and flutter; BC: Breast cancer; CKD: Chronic kidney disease due to several causes; CRC: Colon and rectum cancer; DT2: Diabetes mellitus type 2; EC: Oesophageal cancer; ENDC: Endocarditis; HHD: Hypertensive heart disease; ICH: Intracerebral haemorrhage; IHD: Ischemic heart diseases; ISTR: Ischemic stroke; SAH: Subarachnoid haemorrhage, SC: Stomach cancer; TBLC: Tracheal, bronchus and lung cancer; otherCVD: other cardiovascular diseases, PUFA: Polyunsaturated fatty acids.

substantial burden in several NCDs in all diets, along with intake of trans-fatty-acids (Fig. 2b). In contrast, keeping the intake of dietary risks within healthy threshold limits may also increase the minutes of healthy life gained. For instance, consuming calcium and milk increases minutes of life gained in colon rectum cancer (CRC), and fruit, whole grains and fibre intake, in Diabetes type II (DT2). The loss of minutes of healthy life in ischemic heart disease (IHD) is mainly attributed to sodium, trans-fatty-acids and processed meat, which are counterbalanced with minutes of healthy life gained from whole grains, fibre, nuts and PUFA, resulting in positive net values in PRU (1.1 min ± 2.3).

3.2. *Optimisation scenarios*

Although optimisations were carefully designed to induce minimal alterations in dietary behaviour, the feasible solutions provided small changes in food intake to meet the nutritional requirements and the set criteria. These changes in food intake vary from a decrease of - 9.1% in WT2 in the *Combined* scenario to a + 36.1% increase in food intake in WT1, *Zero AWL* scenario. Fig. 3 illustrates each dietary pattern's daily food intake in grams and optimisation scenarios broken down by food group categories. It is possible to see that optimisation scenarios (*25%*

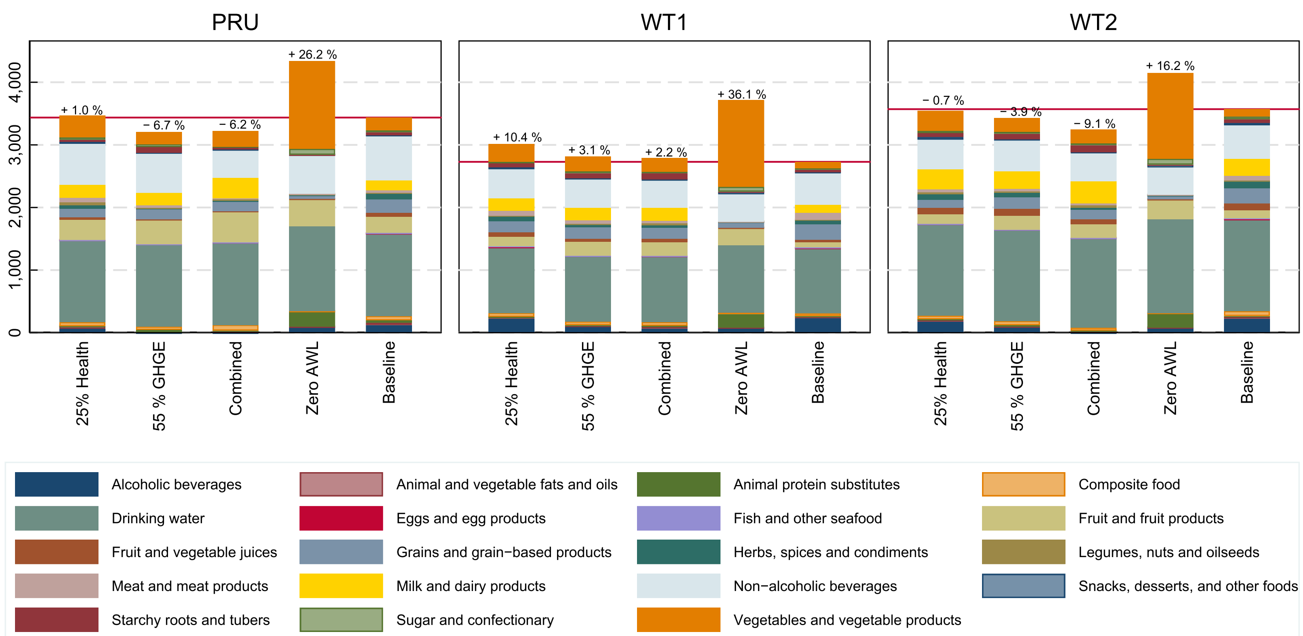

Fig. 3. Daily food intake (in grams) per person of optimised scenarios grouped by food categories compared to the baseline (observed diets). Stack bars represent the sum of intake per food category. Bar height indicates the total amount of food consumed per day in grams with percentages of change against the baseline on the top of each bar. Bar colours follow the order presented in the legend (left to right). WT1: Western-type 1; WT2: Western-type 2; PRU: Prudent; Zero AWL: Zero animal welfare loss; 25% Health: 25% health improvement in all dietary risk factors; 55% GHGE: 55% greenhouse gases emission reductions; Combined: a combination of scenario 55% GHGE and 25% Health.

Health, *55% GHGE* and *Combined*) provided small changes in overall dietary intake, except *Zero AWL*, which increased food intake for all diets due to a higher intake of vegetables and vegetable products and removed all animal products from the diet, which might impact consumer acceptance. Shifting to a completely plant-based diet implies greater motivational reasons, e.g. political or ethical concerns, to support drastic dietary changes in consumer behaviour.

Regarding food composition, all optimisations led to a 100% reduction in fish and seafood intake due to the higher impact on animal welfare loss, except *25% Health*, which increased 64% in WT1. Scenarios also presented a reduction in intake of condiments (containing high sodium levels), 83% less in PRU, 49% less in WT1 and 56% less in WT2, due to the impact on human health. PRU, WT1 and WT2 presented a reduction in intake of meat and meat products by 25%, 62% and 35%, respectively, to allow GHGE reductions. The *Combined* and *55% GHGE* scenarios presented an increased intake of egg and egg products, from an initial intake of 0.08 g to 15.3 g in PRU, 0.14 g to 23.4 g in WT1, and 0.15 g to 8.6 g in WT2. Although changes in egg consumption are substantial because the initial intake was too low (<0.2 g), dietary shifts represent an intake of less than one egg per day, thus realistic from a consumer perspective. *Zero AWL* increased the intake of animal protein substitutes, particularly in WT1 (50-time fold) and WT2 (18-time fold), which is around 230 g/day to compensate for meat reduction. All scenarios increased the intake of fruit and fruit products from 58% in PRU to 163% in WT1, except *Zero AWL*, which maintained the intake. Scenarios induced a remarkable increase in the intake of vegetables (173% to 352% on average) and legumes, nuts, and oilseeds (107% total average). Except for *Zero AWL*, scenarios led to increased milk and dairy intake to satisfy nutritional and health constraints (5 to 107% change).

In most cases, optimisation helps reduce the impacts across OH dimensions. However, trade-offs arise in some of the indicators. The *55% GHGE* and *Combined* scenarios resulted in the most significant reductions across environmental impact categories. WT2 benefits from greater reductions in environmental impacts. WT1 showed a considerable decrease in fine particular matter formation (Fig. 4d), marine eutrophication (Fig. 4i) and terrestrial acidification (Fig. 4j). Water consumption (Fig. 4k) and freshwater eutrophication (Fig. 4f) decreased moderately in PRU. *25% Health* contributed the least to improving environmental impact categories and worsened fossil resource scarcity by 7.9% in WT1 (Fig. 4e), land use by 13% in PRU (Fig. 4h) and water consumption in all diets, from 6% in WT2 to 28% in WT1 (Fig. 4k). Likewise, *Zero AWL* also increased water consumption in all diets (24% in PRU to 54% in WT1) (Fig. 4k), and in PRU, fossil resource scarcity (Fig. 4e) by 9.9% and global warming by 1.4% (Fig. 4g).

As for animal welfare loss, WT2 and PRU show greater reductions in AL, ALYS, and MAL, whereas WT1 shows lower reductions after optimisations for the same indicators. All animal welfare indicators were reduced (100%) in *Zero AWL* because this scenario is a purely plant-based diet. *25% Health* did not present significant reductions and increased ALYS by 12.1% in WT1 (Fig. 4b). The *Combined* and *55% GHGE* scenarios decreased AL, as *Zero AWL* does (Fig. 4a). *Combined* scenario showed more substantial reductions for ALYS and MAL than *55% GHGE* (Fig. 4b, Fig. 4c).

Since we evaluated the impact reduction to be consistent with the other indicators, impact reduction in human health meant lifting HENI scores from the negative state (life minutes lost) to a positive state (life minutes gained). Results are shown in change of minutes of healthy life gained against the observed diet (Fig. 4l). All scenarios improved overall human health in all diets, but the *Combined* and *Zero AWL* scenarios scored higher. The *Combined* scenario showed a higher HENI change in PRU of 72 min of healthy life in PRU (from -9 min of life lost to +64 life minutes of life gained). *Zero AWL* showed notable higher HENI changes of 67 min of healthy life in WT1 (from -18 min of life lost to +49 life minutes of life gained) and of 71 min of healthy life in WT2 (from -18 min of life lost to +53 life minutes of life gained). This outcome highlights the importance of plant-based foods on improving human health, aligned with a reduction or elimination of animal-based products. *25%*

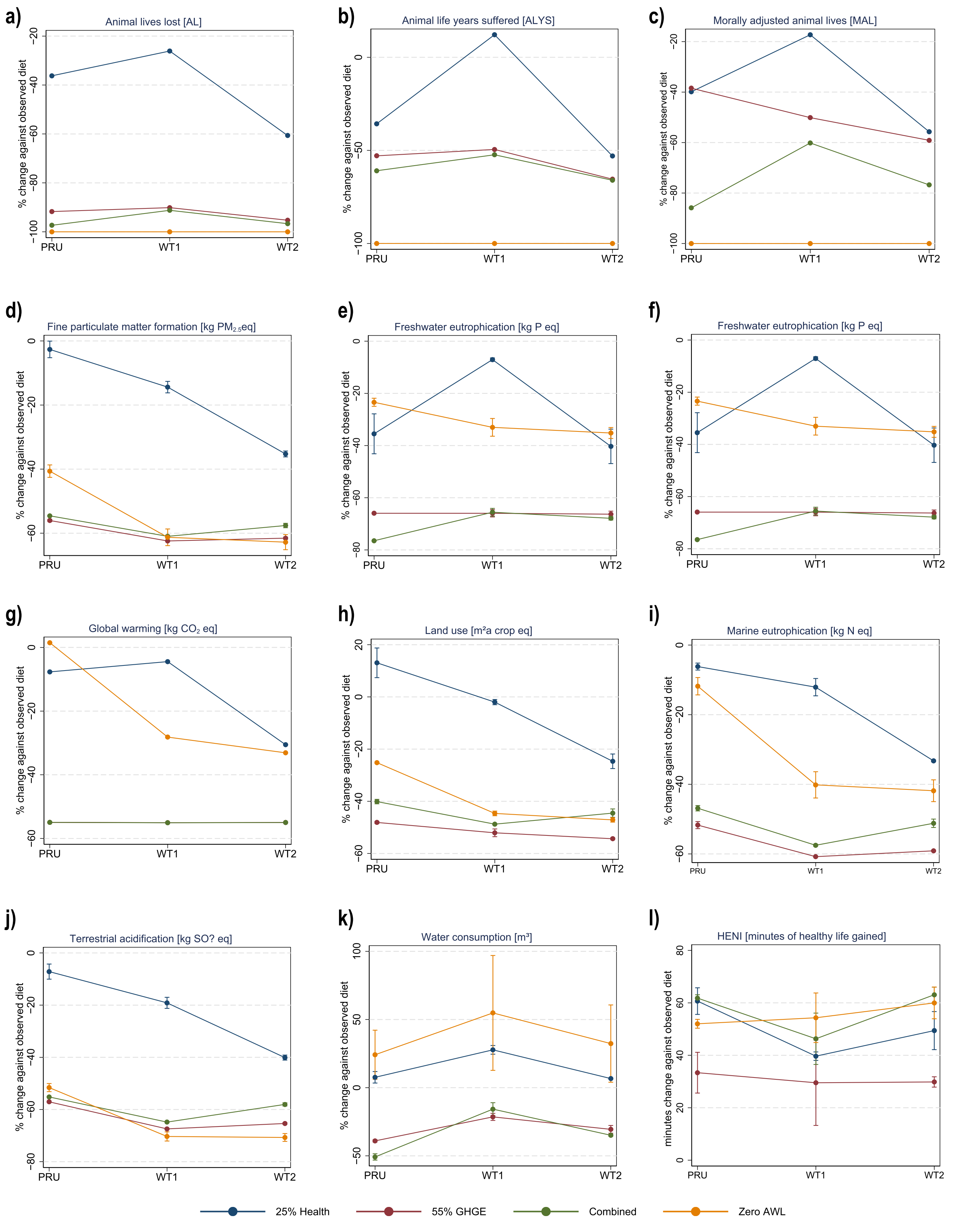

Fig. 4. Percentage change against the observed diets of optimisation scenarios. Dots represent the plot of predicted margins resulting from robust regression analysis of the correlations between dietary patterns and optimisation scenarios' changes against the baseline diet. Standard error bars are present when $p < 0.05$. An increase along the y-axis implies worsening the impacts through most of the impact categories. For HENI, changes are displayed in minutes of healthy life gained against the observed diets, meaning improvement of health along the y-axis. WT1: Western-type 1; WT2: Western-type 2; PRU: Prudent; HENI: Health Nutritional Index; Zero AWL: Zero animal welfare loss; 25% Health: improvement of health indicators by 25%; 55% GHGE: 55% GHGE reductions; Combined: a combination of 55% GHGE and 25% Health.

Health scenario also improved HENI scores impact but less than the *Combined and Zero AWL*. *55% GHGE* changed HENI the least compared to the other scenarios, which means that aiming for GHGE reductions has a limited improvement human health.

4. Discussion

Optimisations identified improved sustainable dietary shifts regarding human health, animal welfare, and the environment while respecting nutritional requirements and small changes in consumption behaviour. Like other studies (Broekema et al., 2020; Kramer et al., 2017), our findings recommend reducing animal-based products while modifying the intake of plant-based ones. Our outcomes suggest a reduction of 41% (on average) of meat and meat products to mitigate 55% GHGE. It might not be necessary to totally eliminate meat from the diet, as moderate consumption can provide beneficial nutrients, and GHGE intensity also varies among the heterogeneous production systems (McAuliffe et al., 2016; Mrówczyńska-Kamińska et al., 2021). However, one must consider the trade-offs related to meat intake, including its association with several chronic diseases, environmental impacts and animal welfare (Qian et al., 2020).

From our assessment, WT1 and WT2 performed worse for environmental and animal welfare than PRU. Yet, PRU had higher sodium levels (from salt intake) than other diets, increasing the risk of hypertension and cardiovascular diseases. A reduction of sodium intake of <4 g/day should be prioritised to provide health gains of 28 min/pers./day. Fish, seafood, and poultry have a higher impact on animal welfare due to the number of animals affected in production systems, corroborating findings from other studies on multidimensional LCAs (Scherer et al., 2019). Nevertheless, the consumption of unprocessed white meat (i.e., poultry, fish) is not a dietary risk, unlike red and processed meat, and has been associated with healthy diets and positive metabolic health outcomes, according to other studies. Additionally, white meat generates less GHGE than ruminant meat (Damigou et al., 2022; Li et al., 2020; Poore and Nemecek, 2018). Therefore, trade-offs must be considered when structuring new optimised diets to achieve “One Health”.

This study collected primary food consumption data at the regional level to capture current food consumption patterns for building realistic scenarios (Vieux et al., 2022). Our findings can inform dietary shifts towards more sustainable Western diets, especially in Germany, where regional socioeconomic and cultural differences largely determine food consumption patterns (Treu et al., 2017). However, the survey’s participant outreach might affect the general applicability of our findings. The sampling strategy did not favour a truly representative population sample, but it increased feasibility and participant consent. The pandemic context in 2020 influenced eating behaviour and self-selection bias. Although the sample is not representative of the whole population, it is homogenous. The survey reached a particular population with similar demographic characteristics in terms of gender (77% women), age, ethnicity, high education level and income. We take caution in overinterpreting our findings in terms of generalization to the general public. Instead, we suggest making dietary shifts based on the pilot sample we collected from a specific population segment.

One potential bias is that the population is predominantly urban, living in a high-income country, has access to the internet and has a particular interest in the survey topic. Several online surveys conducted during the pandemic showed similar bias due to the dissemination via social media, telephone messaging and emails, which does not control self-selection bias (Singh and Sagar, 2021). Participants’ interests in the topic can be the main reason behind self-selection bias in online surveys conducted during COVID-19 (Donzowa et al., 2023). Nevertheless, regional primary food consumption data remains relevant for assessing dietary shifts as nearby neighbourhoods indicate income level and dietary patterns (LeDoux and Vojnovic, 2014). Results will likely change if the assessment incorporates representative samples, and consequently, food intake changes. Other studies using several sample sizes also showed Western type of diets in several European countries, in which reducing animal-based consumption is expected to improve overall sustainability (Broekema et al., 2020; Irz et al., 2019; Meier and Christen, 2013; Treu et al., 2017).

Optimisation of HENI is challenging due to the assumed linearity of DRFs, meaning that modifying the intake would change impacts proportionally. For a few modifications, this might not be a potential issue; nevertheless, with larger intake modifications, improvements for a log-linear model are necessary. We also assumed a coefficient of variation from the NHANES to characterize DRFs. However, the sensitivity analysis showed little DRF variation within a wide coefficient variation (**SI, S5**). Additionally, sodium mediated by high blood pressure differed from direct sodium intake because hypertension is a risk factor for several diseases. More sophisticated DRFs, combining other behavioural or metabolic risk factors (e.g., body mass index) would better capture other correlations between diet and disease risk in LCA (Weidema and Stylianou, 2020). Ortenzi et al. (2023) highlighted the methodological limitations of HENI, which missed the importance of nutrient density and the consumption of ultra-processed food, which is intrinsically linked to the healthiness of food consumption.

The scenarios *55% GHGE* and *Combined* improved the performance among indicators; however, *55% GHGE* had a limited improvement on human health. *25% Health* is the least promising scenario, often worsening environmental and animal welfare indicators. This highlights the trade-offs commonly reported between environment and health, meaning that only a healthy diet does not comply with the planetary boundaries without additional sustainable shifts along the supply chains and substantial socioeconomic changes (Poore and Nemecek, 2018; Steenson and Buttriss, 2021). However, adhering to a planetary health diet in high-income countries would yield a 61% GHGE reduction of current annual agricultural emissions (Sun et al., 2022).

The developed *Combined* scenario would potentially fit into the 55% reduction targets of the EU Green Deal (European Commission, 2021) while promoting health (25% improvement of human health indicators) and reducing animal welfare loss substantially by 52-97% among the dietary patterns. To achieve this target reduction, this scenario favoured other sources of protein, e.g., eggs, dairy and meat substitutes and increased the intake of vegetables, fruits, legumes and nuts, suggesting flexitarian and vegetarian diets. Changing protein sources could impact the acceptance of new dietary habits. This is due to factors such as affordability, accessibility, cultural acceptability, and tailoring to specific population needs in terms of nutrition, sustainability, demographics, and economic development (Drewnowski et al., 2020; Steenson and Buttriss, 2020). A recent nutrition study in Germany showed that adopting vegetarian alternatives is age-dependent, to which the younger population is more likely to adhere (BMEL, 2021). Further research looking into age-dependent sustainability assessment of food consumption could identify a target population to address dietary interventions.

Large-scale dietary shifts may provoke supply and demand adjustments across agri-food markets and diversified sustainability outcomes. This requires global economic models and consequential LCA to simulate international trade and market behaviour in response to exogenous shocks (Springmann et al., 2016; van Meijl et al., 2020). It is important to note that apart from GHGE reductions, often highlighted in the political sphere, other relevant impacts on biodiversity, for example, are usually disregarded and should have the same level of attention (Engström et al., 2008).

Zero AWL could be feasible from the optimisation approach, provided there was a more diverse list of food items than the ones in this analysis and co-production allocation was considered part of the model. A limited number of food items under several constraints may exacerbate results, deviating from the realistic behaviour. This explains the significant change in leeks and cabbage intake, which increased fossil resource scarcity, global warming, water consumption. Individual-level modelling approach varies food item intake, offering a higher acceptance with a specific reduction target. However, broader dietary flexibility could be better achieved using a population target goal (Rocabois et al., 2022). On the one hand, removing animal-based products from the diet can reduce the overall carbon footprint substantially, on the other, may lead to nutritional inadequacies without introducing suitable substitutes (Humpenöder et al., 2022; Zhang et al., 2023).

Animal welfare considerations in LCAs have become highly important given Germany's animal welfare initiative and labelling act to meet EU animal welfare policy and consumer aspirations (BMEL, 2022; European Court of Auditors, 2018). Our results indicated fish as the main contributor to animal welfare impact, which could explain why its consumption was eliminated in optimised scenarios. This arises partly from the framework definition and modelling approaches (Scherer et al., 2018) that smaller animals have a greater life loss than larger animals. Also, due to the unethical production practices in industrial aquaculture, including high mortality rate, decreased environmental conditions, and health issues (Berlinghieri et al., 2021; Størkersen et al., 2021). An ethical consensus is still needed in animal welfare assessment and a better resolution of available products (only a few fish and seafood types were considered, i.e., salmon, trout, and shrimp). This study could be improved by incorporating other fish and seafood species in LCI to enhance the resolution of results.

Reducing animal welfare loss in dietary scenarios without removing animal-based products derives from the adjustment of animal products. The choice of animal type has implications. Larger animals generate more kg of food by animal, compared to small animals, which require more animal lives to generate the same functional unit. Ethical questions arise regarding the utility of animals in their purpose to serve us versus their moral intrinsic value of life (Killoren and Streiffer, 2020). Humans show more empathy and compassion for animals whose suffering similarities they can relate to, such as mammals, rather than insects, fish or seafood (Miralles et al., 2019). Considering the high sensitivity of animal welfare issues, often neglected in sustainability assessments, it is important to highlight strategies for reducing animal welfare loss. The type of protein source influences the impact of animal welfare. The complete removal of animal-based- products or the selection of animals that affect fewer animal lives would ultimately reduce animal welfare outcomes derived from dietary choices. Another way, though, is improving the technology of production systems to respect the natural behaviour of animals, thus improving animal welfare. These technologies would eventually change the overall estimation of animal welfare indicators. Some examples are improving animal life quality and nutrition, reducing disease incidence due to animal behaviour and adaptation, improving environmental conditions, eliminating animals from production systems through in-vitro lab meat, and alternatives to animal-sourced products (Croney et al., 2018; Lemes et al., 2021; Orihuela, 2021; UNEP, 2023).

Additional methodological limitations derive from LCI data in Optimeal®. Trade data is relatively old (2009-2013). However, improving with more updated import mixes is out of scope, as this would imply reassessing LCA for each product. Nevertheless, import mixes for agricultural commodities are assumed to be consistent with the trade data for the Netherlands and, therefore, representative of the Rhine-Ruhr Metropolis due to geographical proximity. Expected changes in environmental footprint will more likely respond to the difference in production systems in the respective exporting countries (Sandström et al., 2018). Other limitations arise from different LCI sources considering different system boundaries due to data limitations. Moreover, minimum vitamin D and B12 requirements should be taken as optimisation constraints since observed diets presented values below daily requirements, which was impossible in this study due to technical limitations.

Moreover, we conducted a sensitivity analysis using linear programming relative to quadratic optimisation to evaluate differences in reduction outcomes represented by predicted margins resulting from robust regression analysis of the correlations between dietary patterns and optimisation changes against the baseline diet. While the quadratic programming provoked small changes in more food items, the linear programming caused greater changes in fewer food items. However, it did not imply a significant change ($p < 0.05$) in outcome. Only water consumption presented a significant difference between the two optimisations because fewer changes occurred in food such as fruit, vegetables, grains, and legumes (see **SI, S6**). Robust linear prediction showed a 36.26% difference ($p < 0.001$) between quadratic and linear programming for water consumption. Individual dietary patterns displayed significant differences in water consumption of 24.72% ($p = 0.003$) in PRU, 51.78% (p < 0.001) in WT1, and 33.34% ($p = 0.001$) in WT2. Minor differences were observed in AL for WT1 of -16.1 ($p = 0.043$) and WT2 of -17.95 (p = 0.001), in MAL only for WT2 of -14.26 difference ($p = 0.005$) and HENI in WT1 of 8.5 min of healthy life difference (p < 0.001) (see **Fig. S2** in **SI**). These minor differences in distinct dietary patterns for AL, MAL and HENI do not represent statistical differences between linear and quadratic programming when the three dietary patterns are included. Additional sensitivity analysis in future studies could be done to improve the robustness of the results, e.g., change in specific assumptions, change in parameter, or additional tests to assess parametric uncertainty (e.g., probabilistic methods).

Finally, despite the contributions of this study to include three relevant dimensions of sustainability, additional efforts are needed to address One Health as a whole, including exploring zoonotic disease risk and other issues in both LCI and LCIA, as this directly affects meat consumption, environmental damage, future health outcomes and possible consequences to sustainability in the post-pandemic (Attwood and Hajat, 2020). Moreover, a better assessment of the sustainability of diets at the regional level requires a more comprehensive and representative sample to inform decision-makers in supporting sustainability goals. This study could be reproduced in another similar or distinct socio-economic context to validate the application of the proposed framework.

5. Conclusions

The major innovation of this study is the employment of an extended LCA framework with indicators for environmental impact, human health and animal welfare to assess and optimise the sustainability of diets in the Rhine-Ruhr Metropolis in 2020. Data on food consumption was collected from 189 participants. Three dietary patterns were observed within the population: PRU, WT1 and WT2. Optimisation scenarios were defined to capture more sustainable food choices, which could potentially be adopted by the population – *55% GHGE, 25% Health, Zero AWL* and *Combined*. The scenarios deliver improvements across the OH dimensions with marginal dietary changes but generate trade-offs. Achieving a 55% GHGE reduction target in line with the EU Green Deal goals is feasible through the *Combined* scenario while promoting human health and reducing animal welfare loss. To meet this ambitious aim, it is necessary to reduce average meat consumption by 41%, compensating with other protein sources, such as eggs, dairy, and plant-based, suggesting a shift towards more flexitarian and vegetarian dietary scenarios. Health concerns about high sodium intake were raised due to the assumed interlinkages of sodium with other metabolic risk factors. HENI should be continuously improved for further integration into LCA, addressing human health attributed to several risk factors. Finally, more comprehensive and consistent sample data on food consumption are needed for a more representative regional and country-level assessment, as well as improving the robustness of the proposed LCA method and indicators to better represent the OH. This assessment rethinks current consumption patterns to prepare for the post-COVID-19 pandemic.

CRediT authorship contribution statement

Juliana Minetto Gellert Paris: Writing – original draft, Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – review & editing, Visualization. **Neus Escobar:** Conceptualization, Methodology, Validation, Writing – review & editing. **Timo Falkenberg:** Conceptualization, Writing – review & editing, Funding acquisition. **Shivam Gupta:** Resources, Software, Writing – review & editing. **Christine Heinzel:** Investigation, Writing – review & editing. **Eliseu Verly Junior:** Resources, Methodology, Software, Validation, Writing – review & editing. **Olivier Jolliet:** Conceptualization, Methodology, Software, Validation, Writing – review & editing. **Christian Borgemeister:** Conceptualization, Writing – review & editing, Funding acquisition, Supervision. **Ute Nöthlings:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

Supplementary data is offered as supplementary information. Any other data not displayed here are available upon request.

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Appendix A. Supplementary data

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References

Aiking, H., de Boer, J., 2020. The next protein transition. Trends Food Sci. Technol. 105, 515–522. https://doi.org/10.1016/j.tifs.2018.07.008.

Angelos, J.A., Arens, A.L., Johnson, H.A., Cadriel, J.L., Osburn, B.I., 2017. One Health in food safety and security education: subject matter outline for a curricular framework. One Health 3, 56–65. https://doi.org/10.1016/j.onehlt.2017.04.001.

Attwood, S., Hajat, C., 2020. How will the COVID-19 pandemic shape the future of meat consumption? Public Health Nutr. 23, 3116–3120. https://doi.org/10.1017/S136898002000316X.

Batlle-Bayer, L., Bala, A., Albertí, J., Xifré, R., Aldaco, R., Fullana-i-Palmer, P., 2020. Food affordability and nutritional values within the functional unit of a food LCA. An application on regional diets in Spain. Resour. Conserv. Recycl. 160, 104856 https://doi.org/10.1016/j.resconrec.2020.104856.

Berlinghieri, F., Panizzon, P., Penry-Williams, I.L., Brown, C., 2021. Laterality and fish welfare - a review. Appl. Anim. Behav. Sci. 236, 105239 https://doi.org/10.1016/j.applanim.2021.105239.

BMEL, 2020. Deutschland, wie es isst. Der BMEL-Ernährungsreport 2020 [WWW Document]. Bundesministerium für Ernährung und Landwirtschaft. URL. https://www.bmel.de/DE/themen/ernaehrung/ernaehrungsreport2020.html (accessed 9.26.23).

BMEL, 2021. Ernährungsreport 2021 [WWW Document]. Bundesministerium für Ernährung und Landwirtschaft. URL. https://www.bmel.de/DE/themen/ernaehrung/ernaehrungsreport2021.html (accessed 9.13.21).

BMEL, 2022. Staatliche Tierhaltungskennzeichnung: Erste Lesung im Bundestag [WWW Document]. Tierhaltungskennzeichnung. URL. https://www.bmel.de/SharedDocs/Pressemitteilungen/DE/2022/179-tierhaltungskennzeichnung.html (accessed 10.6.23).

Bonnet, C., Bouamra-Mechemache, Z., Réquillart, V., Treich, N., 2020. Viewpoint: regulating meat consumption to improve health, the environment and animal welfare. Food Policy 97, 101847. https://doi.org/10.1016/j.foodpol.2020.101847.

Broekema, R., Blonk, H., Koukouna, E., van Paassen, M., 2019. Optimeal EU dataset [WWW Document]. URL. https://www.optimeal.nl/ (accessed 10.6.23).

Broekema, R., Tyszler, M., van't Veer, P., Kok, F.J., Martin, A., Lluch, A., Blonk, H.T., 2020. Future-proof and sustainable healthy diets based on current eating patterns in the Netherlands. Am. J. Clin. Nutr. 112, 1338–1347. https://doi.org/10.1093/ajcn/nqaa217.

Croney, C., Muir, W., Ni, J.-Q., Widmar, N.O., Varner, G., 2018. An overview of engineering approaches to improving agricultural animal welfare. J. Agric. Environ. Ethics 31, 143–159. https://doi.org/10.1007/s10806-018-9716-9.

Damigou, E., Kosti, R.I., Panagiotakos, D.B., 2022. White meat consumption and cardiometabolic risk factors: a review of recent prospective cohort studies. Nutrients 14, 5213. https://doi.org/10.3390/nu14245213.

de Boer, J., Aiking, H., 2022. Do EU consumers think about meat reduction when considering to eat a healthy, sustainable diet and to have a role in food system change? Appetite 170, 105880. https://doi.org/10.1016/j.appet.2021.105880.

Deblitz, C., Agethen, K., Efken, J., Rohlmann, C., Verhaagh, Mandes, Ellßel, R., Tergast, H., Hansen, H., von Davier, Z., Schütte, J., Thobe, P., Gröner, C., 2022. Livestock Farming and Meat Production in Germany [WWW Document]. Johann Heinrich von Thünen Institute Federal Research Institute for Rural Areas, Forestry and Fisheries. URL https://www.thuenen.de/en/thuenen-topics/livestock-farming-and-aquaculture/nutztierhaltung-und-fleischproduktion-in-deutschland (accessed 10.6.23).

Destatis, 2022a. Bevölkerung (Zensus): Deutschlabd, Stichtag, Geschelecht, Altersgruppen [WWW Document]. GENESIS-Online. URL. https://www-genesis.destatis.de/genesis/online?operation=themes&levelindex=0&levelid=1659108158237&code=12#abreadcrumb.

Destatis, 2022b. Ausländer: Deutschland, Stichtag, Geschlecht, Altersjahre, Ländergruppierungen/Staatsangehörigkeit [WWW Document]. GENESIS-Online. URL. https://www-genesis.destatis.de/genesis/online?operation=themes&levelindex=0&levelid=1659108158237&code=12#abreadcrumb.

Donzowa, J., Perrotta, D., Zagheni, E., 2023. Assessing Self-Selection Biases in Online Surveys: Evidence from the COVID-19 Health Behavior Survey. https://doi.org/10.4054/MPIDR-WP-2023-047.

Drewnowski, A., Monterrosa, E.C., de Pee, S., Frongillo, E.A., Vandevijvere, S., 2020. Shaping physical, economic, and policy components of the food environment to create sustainable healthy diets. Food Nutr. Bull. 41, 74S–86S. https://doi.org/10.1177/0379572120945904.

Durlinger, Koukouna, E., Broekema, R., Scholten, J., van Mike, P., 2017a. Agri-footprint 4.0 - Part 2: Description of data [WWW Document]. URL. https://simapro.com/wp-content/uploads/2018/02/Agri-Footprint-4.0-Part-2-Description-of-data.pdf (accessed 10.6.23).

Durlinger, Koukouna, E., Broekema, R., Scholten, J., van Mike, P., 2017b. Agri-footprint 4.0. Part 1: Methodology and basic principles [WWW Document]. URL. https://simapro.com/wp-content/uploads/2016/01/agri-footprint-methodology-and-basic-principles.pdf (accessed 10.6.23).

EFSA, 2018a. The EFSA Comprehensive European Food Consumption Database [WWW Document]. European Food Safety Authority. URL. http://www.efsa.europa.eu/en/food-consumption/comprehensive-database (accessed 10.6.23).

EFSA, 2018b. Summary of Tolerable Upper Intake Levels - version 4. Overview on Tolerable Upper Intake Levels as derived by the Scientific Committee on Food (SCF) and the EFSA Panel on Dietetic Products, Nutrition and Allergies (NDA) [WWW Document]. URL. https://www.efsa.europa.eu/sites/default/files/assets/UL_Summary_tables.pdf (accessed 10.5.21).

EFSA, 2019a. EFSA Food composition database [WWW Document]. URL. https://www.efsa.europa.eu/en/data-report/food-composition-data (accessed 10.6.23).

EFSA, 2019b. Dietary Reference Values for the EU [WWW Document]. European Food Safety Authority. URL. https://multimedia.efsa.europa.eu/drvs/index.htm (accessed 10.15.21).

Engström, R., Nilsson, M., Finnveden, G., 2008. Which environmental problems get policy attention? Examining energy and agricultural sector policies in Sweden. Environ. Impact Assess. Rev. 28, 241–255. https://doi.org/10.1016/j.eiar.2007.10.001.

European Commission, 2018. Product Environmental Footprint Category Rules. Version 6.3 [WWW Document]. URL. https://eplca.jrc.ec.europa.eu/permalink/PEFCR_guidance_v6.3-2.pdf (accessed 10.6.23).

European Commission, 2020. Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and the Committee of the Regions: A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system [WWW Document]. COM(2020) 381 final. URL. https://agridata.ec.europa.eu/Qlik_Downloads/Jobs-Growth-sources.htm (accessed 5.3.21).

European Commission, 2021. 2030 Climate Target Plan [WWW Document]. European Green Deal. URL. https://ec.europa.eu/clima/eu-action/european-green-deal/2030-climate-target-plan_en (accessed 8.1.22).

European Court of Auditors, 2018. Animal welfare in the EU: closing the gap between ambitious goals and practical implementation [WWW Document]. URL. https://www.eca.europa.eu/Lists/ECADocuments/SR18_31/SR_ANIMAL_WELFARE_EN.pdf (accessed 8.5.22).

Falkenberg, T., Paris, J.M.G., Patel, K., Arredondo, A.M.P., Schmiege, D., Yasobant, S., 2022. Operationalizing the One Health Approach in a Context of Urban Transformations. Springer, Singapore, pp. 95–102. https://doi.org/10.1007/978-981-19-2523-8_14.

FAOSTAT, 2013. FAO Trade Statistics [WWW Document]. Food and Agriculture Organization of the United Nations. URL. http://www.fao.org/faostat/en/#data.

FAOSTAT, 2023. Food Balances (2010-) [WWW Document]. Food and Agriculture Organization of the United Nations. URL. https://www.fao.org/faostat/en/#data/FBS (accessed 10.16.23).

Ferreira, J.G., Andersen, J.H., Borja, A., Bricker, S.B., Camp, J., Cardoso da Silva, M., Garcés, E., Heiskanen, A.-S., Humborg, C., Ignatiades, L., Lancelot, C., Menesguen, A., Tett, P., Hoepffner, N., Claussen, U., 2011. Overview of eutrophication indicators to assess environmental status within the European Marine Strategy Framework Directive. Estuar. Coast. Shelf Sci. 93, 117–131. https://doi.org/10.1016/j.ecss.2011.03.014.

Garcia, R., 2017. 'One Welfare': a framework to support the implementation of OIE animal welfare standards. Bull. de l'OIE 2017, 3–8. https://doi.org/10.20506/bull.2017.1.2588.

Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B.L., Fetzer, I., Jalava, M., Kummu, M., Lucht, W., Rockström, J., Schaphoff, S., Schellnhuber, H.J., 2020. Feeding ten billion people is possible within four terrestrial planetary boundaries. Nat. Sustain. 3 (3), 200–208. https://doi.org/10.1038/s41893-019-0465-1.

Gibin, D., Simonetto, A., Zanini, B., Gilioli, G., 2022. A framework assessing the footprints of food consumption. An application on water footprint in Europe. Environ. Impact Assess. Rev. 93, 106735 https://doi.org/10.1016/j.eiar.2022.106735.

Goess, S., de Jong, M., Meijers, E., 2016. City branding in polycentric urban regions: identification, profiling and transformation in the Randstad and Rhine-Ruhr. Eur. Plan. Stud. 24, 2036–2056. https://doi.org/10.1080/09654313.2016.1228832.

Global Burden of Disease Collaborative Network, 2020. Global Burden of Disease Study 2019 (GBD 2019). Global Health Data Exchange (GHDx). Seatle, United States: Institute for Health Metrics and Evaluation (IHME) [WWW Document] URL (accessed 3.25.24) https://ghdx.healthdata.org/.

Harttig, U., 2021. EPIC-Potsdam Food Frequency Questionnaire- II [WWW Document]. Deutsches Institut für Ernährungsforschung Potsdam-Rehbrücke (DIfE). URL. https://sms.dife.de/.

Helander, H., Bruckner, M., Leipold, S., Petit-Boix, A., Bringezu, S., 2021. Eating healthy or wasting less? Reducing resource footprints of food consumption. Environ. Res. Lett. 16, 054033 https://doi.org/10.1088/1748-9326/abe673.

Heller, M.C., Keoleian, G.A., Willett, W.C., 2013. Toward a life cycle-based, diet-level framework for food environmental impact and nutritional quality assessment: a critical review. Environ. Sci. Technol. 47, 12632–12647. https://doi.org/10.1021/es4025113.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

Humpenöder, F., Bodirsky, B.L., Weindl, I., Lotze-Campen, H., Linder, T., Popp, A., 2022. Projected environmental benefits of replacing beef with microbial protein. Nature 605, 90–96. https://doi.org/10.1038/s41586-022-04629-w.

IBM Corp, 2021. IBM SPSS Statistics for Windows, Version 28.0.

IKM, 2022. Rhine-Ruhr Metropolitan Region [WWW Document]. Initiativkreis Europäische Metropolregionen in Deutschland, URL. https://deutsche-metropolregionen.org/metropolregion-rhein-ruhr/?lang=en (accessed 7.5.22).

International Dairy Federation, 2016. Bulletin of the IDF N° 485/2016: The World Dairy Situation 2016 [WWW document]. Bulletin of the IDF No. 485/2016, p. 259. URL https://shop.fil-idf.org/products/world-dairy-situation-2016 (accessed 3.25.24).

Irz, X., Jensen, J.D., Leroy, P., Réquillart, V., Soler, L.-G., 2019. Promoting climate-friendly diets: what should we tell consumers in Denmark, Finland and France? Environ. Sci. Pol. 99, 169–177. https://doi.org/10.1016/j.envsci.2019.05.006.

ISO, 2006a. Environmental management — life cycle assessment — principles and framework. International Standard ISO 14040:2006(E).

ISO, 2006b. Environmental management — Life cycle assessment — Requirements and guidelines. International Standard ISO 14044:2006(E).

JCR-IES, 2012. ELCD Database [WWW Document]. URL Joint Research Centre Data Catalogue (accessed 10.6.23).

Jolliet, O., 2022. Integrating dietary impacts in food life cycle assessment. Front. Nutr. 9 https://doi.org/10.3389/fnut.2022.898180.

Killoren, D., Streiffer, R., 2020. Utilitarianism about animals and the moral significance of use. Philos. Stud. 177, 1043–1063. https://doi.org/10.1007/s11098-018-01229-1.

Kramer, G.F., Tyszler, M., Veer, P., van't Blonk, H., 2017. Decreasing the overall environmental impact of the Dutch diet: how to find healthy and sustainable diets with limited changes. Public Health Nutr. 20, 1699–1709. https://doi.org/10.1017/S1368980017000349.

Kramer, G.F.H., Martinez, E.V., Espinoza-Orias, N.D., Cooper, K.A., Tyszler, M., Blonk, H., 2018. Comparing the performance of bread and breakfast cereals, dairy, and meat in nutritionally balanced and sustainable diets. Front. Nutr. 5, 1–9. https://doi.org/10.3389/fnut.2018.00051.

Lebov, J., Grieger, K., Womack, D., Zaccaro, D., Whitehead, N., Kowalcyk, B., MacDonald, P.D.M., 2017. A framework for One Health research. One Health 3, 44–50. https://doi.org/10.1016/j.onehlt.2017.03.004.

LeDoux, T.F., Vojnovic, I., 2014. Examining the role between the residential neighborhood food environment and diet among low-income households in Detroit, Michigan. Appl. Geogr. 55, 9–18. https://doi.org/10.1016/J.APGEOG.2014.08.006.

Lemes, A.P., Garcia, A.R., Pezzopane, J.R.M., Brandão, F.Z., Watanabe, Y.F., Cooke, R.F., Sponchiado, M., de Paz, C.C.P., Camplesi, A.C., Binelli, M., Gimenes, L.U., 2021. Silvopastoral system is an alternative to improve animal welfare and productive performance in meat production systems. Sci. Rep. 11, 14092. https://doi.org/10.1038/s41598-021-93609-7.

Li, N., Wu, X., Zhuang, W., Xia, L., Chen, Y., Wu, C., Rao, Z., Du, L., Zhao, R., Yi, M., Wan, Q., Zhou, Y., 2020. Fish consumption and multiple health outcomes: umbrella review. Trends Food Sci. Technol. 99, 273–283. https://doi.org/10.1016/j.tifs.2020.02.033.

McAuliffe, G.A., Chapman, D.V., Sage, C.L., 2016. A thematic review of life cycle assessment (LCA) applied to pig production. Environ. Impact Assess. Rev. 56, 12–22. https://doi.org/10.1016/j.eiar.2015.08.008.

Meier, T., Christen, O., 2013. Environmental impacts of dietary recommendations and dietary styles: Germany as an example. Environ. Sci. Technol. 47, 877–888. https://doi.org/10.1021/es302152v.

Miralles, A., Raymond, M., Lecointre, G., 2019. Empathy and compassion toward other species decrease with evolutionary divergence time. Sci. Rep. 9, 19555. https://doi.org/10.1038/s41598-019-56006-9.

Mrówczyńska-Kamińska, A., Bajan, B., Pawłowski, K.P., Genstwa, N., Zmyślona, J., 2021. Greenhouse gas emissions intensity of food production systems and its determinants. PLoS One 16, e0250995. https://doi.org/10.1371/journal.pone.0250995.

Murray, C.J.L., Aravkin, A.Y., Zheng, P., Abbafati, C., Abbas, K.M., Abbasi-Kangevari, M., Abd-Allah, F., et al., 2020. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet 396, 1223–1249. https://doi.org/10.1016/S0140-6736(20)30752-2.

Nemecek, T., Jungbluth, N., Canals, L.M., Schenck, R., 2016. Environmental impacts of food consumption and nutrition: where are we and what is next? Int. J. Life Cycle Assess. 21, 607–620. https://doi.org/10.1007/s11367-016-1071-3.

Neuhauser, H.K., Adler, C., Rosario, A.S., Diederichs, C., Ellert, U., 2015. Hypertension prevalence, awareness, treatment and control in Germany 1998 and 2008–11. J. Hum. Hypertens. 29, 247–253. https://doi.org/10.1038/jhh.2014.82.

Nöthlings, U., Hoffmann, K., Bergmann, M.M., Boeing, H., 2007. Fitting portion sizes in a self-administered food frequency questionnaire. J. Nutr. 137, 2781–2786. https://doi.org/10.1093/jn/137.12.2781.

Orihuela, A., 2021. Review: management of livestock behavior to improve welfare and production. Animal 15, 100290. https://doi.org/10.1016/j.animal.2021.100290.

Ortenzi, F., McAuliffe, G.A., Leroy, F., Nordhagen, S., van Vliet, S., del Prado, A., Beal, T., 2023. Can we estimate the impact of small targeted dietary changes on human health and environmental sustainability? Environ. Impact Assess. Rev. 102, 107222 https://doi.org/10.1016/j.eiar.2023.107222.

Paris, J.M.G., Falkenberg, T., Nöthlings, U., Heinzel, C., Borgemeister, C., Escobar, N., 2022a. Changing dietary patterns is necessary to improve the sustainability of Western diets from a One Health perspective. Sci. Total Environ. 811, 151437 https://doi.org/10.1016/j.scitotenv.2021.151437.

Paris, J.M.G., Falkenberg, T., Nöthlings, U., Heinzel, C., Borgemeister, C., Escobar, N., 2022b. Corrigendum to "Changing dietary patterns is necessary to improve the sustainability of Western diets from a One Health perspective" [Sci. Total Environ. 811 (2022)/151437]. Sci. Total Environ. 840, 156616. https://doi.org/10.1016/j.scitotenv.2022.156616.

Pink, A.E., Stylianou, K.S., Ling Lee, L., Jolliet, O., Cheon, B.K., 2022. The effects of presenting health and environmental impacts of food on consumption intentions. Food Qual. Prefer. 98, 104501 https://doi.org/10.1016/j.foodqual.2021.104501.

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 1979 (360), 987–992. https://doi.org/10.1126/SCIENCE.AAQ0216/SUPPL_FILE/AAQ0216_DATAS2.XLS.

Qian, F., Riddle, M.C., Wylie-Rosett, J., Hu, F.B., 2020. Red and processed meats and health risks: how strong is the evidence? Diabetes Care 43, 265–271. https://doi.org/10.2337/dci19-0063.

Ridoutt, B., 2021. Bringing nutrition and life cycle assessment together (nutritional LCA): opportunities and risks. Int. J. Life Cycle Assess. 26, 1932–1936. https://doi.org/10.1007/s11367-021-01982-2.

Ridoutt, B.G., Baird, D., Hendrie, G.A., 2021. Diets within planetary boundaries: what is the potential of dietary change alone? Sustain Prod Consum 28, 802–810. https://doi.org/10.1016/j.spc.2021.07.009.

RIVM, 2021. NEVO-online versie 2021 7.0 [WWW Document]. URL. https://www.rivm.nl/documenten/nevo-online-versie.

Rocabois, A., Tompa, O., Vieux, F., Maillot, M., Gazan, R., 2022. Diet optimization for sustainability: INDIGOO, an innovative multilevel model combining individual and population objectives. Sustainability (Switzerland) 14. https://doi.org/10.3390/su141912667.

Roy, P.-O., Azevedo, L.B., Margni, M., van Zelm, R., Deschênes, L., Huijbregts, M.A.J., 2014. Characterization factors for terrestrial acidification at the global scale: a systematic analysis of spatial variability and uncertainty. Sci. Total Environ. 500–501, 270–276. https://doi.org/10.1016/j.scitotenv.2014.08.099.

Sandström, V., Valin, H., Krisztin, T., Havlík, P., Herrero, M., Kastner, T., 2018. The role of trade in the greenhouse gas footprints of EU diets. Glob. Food Sec. 19, 48–55. https://doi.org/10.1016/j.gfs.2018.08.007.

Scherer, L., Tomasik, B., Rueda, O., Pfister, S., 2018. Framework for integrating animal welfare into life cycle sustainability assessment. Int. J. Life Cycle Assess. 23, 1476–1490. https://doi.org/10.1007/s11367-017-1420-x.

Scherer, L., Behrens, P., Tukker, A., 2019. Opportunity for a dietary win-win-win in nutrition, environment, and animal welfare. One Earth 1, 349–360. https://doi.org/10.1016/j.oneear.2019.10.020.
Schmiege, D., Perez Arredondo, A.M., Ntajal, J., Minetto Gellert Paris, J., Savi, M.K., Patel, K., Yasobant, S., Falkenberg, T., 2020. One Health in the context of coronavirus outbreaks: a systematic literature review. One Health 10, 100170. https://doi.org/10.1016/j.onehlt.2020.100170.
Singh, S., Sagar, R., 2021. A critical look at online survey or questionnaire-based research studies during COVID-19. Asian J. Psychiatr. 65, 102850 https://doi.org/10.1016/j.ajp.2021.102850.
Springmann, M., Godfray, H.C.J., Rayner, M., Scarborough, P., 2016. Analysis and valuation of the health and climate change cobenefits of dietary change. Proc. Natl. Acad. Sci. 113, 4146–4151. https://doi.org/10.1073/pnas.1523119113.
Steenson, S., Buttriss, J.L., 2020. The challenges of defining a healthy and 'sustainable' diet. Nutr. Bull. 45, 206–222. https://doi.org/10.1111/nbu.12439.
Steenson, S., Buttriss, J.L., 2021. Healthier and more sustainable diets: what changes are needed in high-income countries? Nutr. Bull. 46, 279–309. https://doi.org/10.1111/nbu.12518.
Størkersen, K.V., Osmundsen, T.C., Stien, L.H., Medaas, C., Lien, M.E., Tørud, B., Kristiansen, T.S., Gismervik, K., 2021. Fish protection during fish production. Organizational conditions for fish welfare. Mar. Policy 129, 104530. https://doi.org/10.1016/j.marpol.2021.104530.
Stylianou, K.S., Fulgoni, V.L., Jolliet, O., 2021. Small targeted dietary changes can yield substantial gains for human health and the environment. Nat Food 2, 616–627. https://doi.org/10.1038/s43016-021-00343-4.
Sun, Z., Scherer, L., Tukker, A., Spawn-Lee, S.A., Bruckner, M., Gibbs, H.K., Behrens, P., 2022. Dietary change in high-income nations alone can lead to substantial double climate dividend. Nat Food 3, 29–37. https://doi.org/10.1038/s43016-021-00431-5.
Talukder, B., vanLoon, G.W., Hipel, K.W., 2022. Planetary health & COVID-19: a multi-perspective investigation. One Health 15, 100416. https://doi.org/10.1016/j.onehlt.2022.100416.
te Pas, C., De Weert, L., Brokema, R., 2021. Towards a sustainable, healthy and affordable Belgian diet. Optimizing the Belgian diet for nutritional and environmental targets [WWW document]. Eat4Change. URL. www.optimeal.nl.
Thoma, G., Tichenor Blackstone, N., Nemecek, T., Jolliet, O., 2022. Life cycle assessment of food systems and diets. In: Food Systems Modelling. Elsevier, pp. 37–62. https://doi.org/10.1016/B978-0-12-822112-9.00004-7.
Treu, H., Nordborg, M., Cederberg, C., Heuer, T., Claupein, E., Hoffmann, H., Berndes, G., 2017. Carbon footprints and land use of conventional and organic diets in Germany. J. Clean. Prod. 161, 127–142. https://doi.org/10.1016/j.jclepro.2017.05.041.
Tyszler, M., Kramer, G., Blonk, H., 2016. Just eating healthier is not enough: studying the environmental impact of different diet scenarios for Dutch women (31–50 years old) by linear programming. Int. J. Life Cycle Assess. 21, 701–709. https://doi.org/10.1007/s11367-015-0981-9.
UN, 2021. Secretary-General's Chair Summary and Statement of Action on the UN Food Systems Summit [WWW Document]. United Nations Food Systems Summit 2021. URL. https://www.un.org/en/food-systems-summit/news/making-food-systems-work-people-planet-and-prosperity.
UNEP, 2023. Frontiers 2023. What's Cooking? An assessment of the potential impacts of selected novel alternatives to conventional animal products. United Nations Environment Programme. https://doi.org/10.59117/20.500.11822/44236.
van Meijl, H., Shutes, L., Valin, H., Stehfest, E., van Dijk, M., Kuiper, M., Tabeau, A., van Zeist, W.-J., Hasegawa, T., Havlik, P., 2020. Modelling alternative futures of global food security: insights from FOODSECURE. Glob. Food Sec. 25, 100358 https://doi.org/10.1016/j.gfs.2020.100358.
Vanham, D., Guenther, S., Ros-Baró, M., Bach-Faig, A., 2021. Which diet has the lower water footprint in Mediterranean countries? Resour. Conserv. Recycl. 171, 105631 https://doi.org/10.1016/j.resconrec.2021.105631.
Vieux, F., Rémond, D., Peyraud, J.-L., Darmon, N., 2022. Approximately half of total protein intake by adults must be animal-based to meet nonprotein, nutrient-based recommendations, with variations due to age and sex. J. Nutr. 152, 2514–2525. https://doi.org/10.1093/jn/nxac150.
von Braun, J., Afsana, K., Fresco, L.O., Hassan, M.H.A., 2023. Food systems: seven priorities to end hunger and protect the planet. In: Science and Innovations for Food Systems Transformation. Springer International Publishing, Cham, pp. 3–9. https://doi.org/10.1007/978-3-031-15703-5_1.
Weidema, B.P., Stylianou, K.S., 2020. Nutrition in the life cycle assessment of foods—function or impact? Int. J. Life Cycle Assess. 25, 1210–1216. https://doi.org/10.1007/s11367-019-01658-y.
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.
Zhang, M., Li, H., Chen, S., Liu, Y., Li, S., 2023. Interrogating greenhouse gas emissions of different dietary structures by using a new food equivalent incorporated in life cycle assessment method. Environ. Impact Assess. Rev. 103, 107212 https://doi.org/10.1016/j.eiar.2023.107212.

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