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# Changing dietary patterns is necessary to improve the sustainability of Western diets from a One Health perspective

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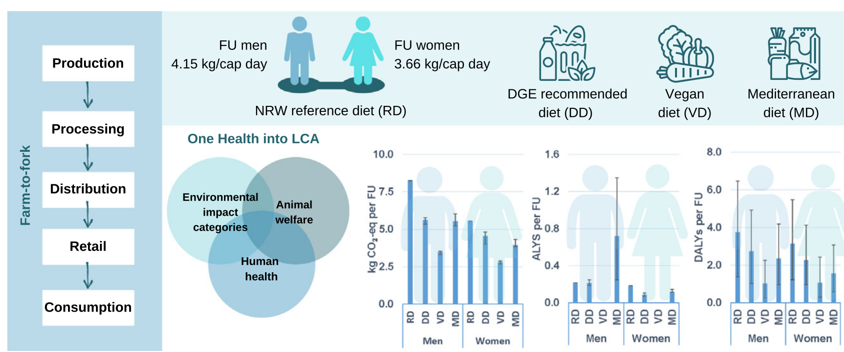
## HIGHLIGHTS

- Sustainability of Western diets in Germany is assessed under a One Health approach.
- Quantitative indicators of animal welfare and human health are integrated into LCA.
- Most impacts of reference diets are driven by animal and ready-to-eat products intake.
- Alternative diets decrease impacts but trade-offs arise among One Health dimensions.
- Critical selection of protein sources is necessary for better One Health performance.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Western diets are associated with multiple environmental impacts and risks to human health. European countries are gradually taking action towards the Farm to Fork Strategy, embracing a Life Cycle Assessment (LCA) perspective to promote the sustainability of food production and consumption. Although LCA enables the comprehensive assessment of environmental impacts, diet-related human health and animal welfare impacts are often underrepresented. This study proposes integrating additional indicators into LCA to evaluate the sustainability of diets under the One Health (OH) approach, which holistically considers interlinked complex health issues between humans, animals and the environment. Human health loss is estimated according to risk factors for non-communicable diseases; while animal welfare is measured as *animal life years suffered*, *loss of animal lives* and *loss of morally-adjusted animal lives*. The extended LCA framework is applied to men and women's reference diets in the German federal state of North Rhine-Westphalia (NRW); compared to three optimized dietary scenarios under nutritional constraints: 1) the national dietary guidelines, 2) a vegan diet (VD) and 3) a Mediterranean diet (MD). Men's reference diet causes greater impacts than women's across OH dimensions due to the higher food consumption, especially of ready-to-eat meals, sausages, meat, and sweetened and alcoholic beverages. Both reference diets are associated with risk factors for cardiovascular diseases, diabetes, stroke and neoplasms. Besides meat, consumption of honey, fish and seafood has the greatest impact on animal welfare, because of the high number of individuals involved. Alternative diets improve the sustainability of food

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consumption in NRW, although trade-offs arise: MD worsens animal suffering due to the higher fish intake; water use increases in both VD and MD due the higher intake of nuts and vegetables. Results highlight the importance of including animal welfare and human health indicators in LCA to better elucidate the potential impacts of diets characterized by the high intake of animal products, from a OH perspective.


## 1. Introduction

The path towards more sustainable and healthier diets constitutes one of humankind's most significant challenges, considering the need to feed a growing world population under the effects of climate change, which currently threatens ecosystems, agriculture and global health (IPCC, 2021; Pörtner et al., 2021; Springmann et al., 2018; Willett et al., 2019). Over the past decades, high-income countries have shifted consumption patterns towards energy-intensive and animal-based foods, unfolding significant environmental damage and the rising prevalence of obesity and non-communicable diseases (NCDs) (Swinburn et al., 2011; Westhoek et al., 2014). On a global level, food consumption represents more than a quarter of anthropogenic greenhouse gas (GHG) emissions – including those from land use and land use change (LUC) – and is a major cause of other environmental impacts, e.g., terrestrial acidification and freshwater (marine) eutrophication (Crippa et al., 2021; Poore and Nemecek, 2018). Moreover, industrial agriculture is directly linked to unbalanced biogeochemical nutrient cycles, natural resource depletion and biodiversity loss in both aquatic and terrestrial ecosystems (Chaudhary and Kastner, 2016; Springmann et al., 2018).

In the European Union (EU), about 950 kg of food are consumed per capita and year; associated with around 27% of the overall EU consumption-based environmental footprints, with animal-based products accounting for a large share (Beylot et al., 2019; Notarnicola et al., 2017b; Sala et al., 2019a, 2019b; Tukker et al., 2011). EU food consumption additionally contributes to global GHG emissions, deforestation and biodiversity loss through agricultural imports and international trade (Castellani et al., 2017; Crenna et al., 2019; Escobar et al., 2020; Sanyé-Mengual et al., 2019). The environmental impacts of food consumption in the EU may have already transgressed global planetary boundaries as for climate change and land use (Sala et al., 2020). In 2020, the Farm to Fork Strategy introduced new targets to achieve sustainable food systems as central points of the EU Green Deal (European Commission, 2020). As a member State, Germany adopted these strategies as part of the national agricultural policy objectives, including nutrition and animal welfare labeling actions, which require impact assessments along the entire supply chain (BMEL, 2020). Nevertheless, Western diets are predominant in Germany, negatively affecting human health and the environment (Helander et al., 2021; Meier et al., 2014). The prevalence of overweight and obesity in the country is about 60% among men and 43% among women (Stehle, 2014). German diets are linked to several diet-related risk factors contributing to cardiovascular diseases, stroke, diabetes and cancer, which are among the top causes of death in the country (GBD 2019, 2020).

Despite the growing environmental, social and ethical concerns about meat consumption in Germany, the country still has one of the largest per-capita meat consumption in the EU, at 59.5 kg per capita and year (BLE, 2020; BMEL, 2019; Sanyé-Mengual et al., 2019). In the last 20 years, Germany's livestock production has become highly intensive, partly driven by increasing international demand, especially from China (Destatis, 2021a; Heinrich Böll Stiftung and BUND, 2016). Around 30% of Germany's total meat production is located in the state of North Rhine-Westphalia (NRW) (DW, 2020). NRW is one of the most intensive livestock producing regions in the EU, having 1,768,289 t of pigs, 212,668 t of cattle and 56,862 t of poultry slaughtered in 2019 (ISN, 2021; IT.NRW, 2020). The intensification of livestock production systems has significant implications for animal health and welfare (Bonnet et al., 2020). Although current animal welfare legislation provides minimum animal protection, there are still complex ethical questions, hurdles and potential trade-offs to overcome (Deutsher Ethikrat, 2020). For instance, the COVID-19 pandemic has worsened animal conditions and made social and health problems in the meat industry more evident (Marchant-Forde and Boyle, 2020). There is a growing consensus that a significant reduction of animal-based products is necessary to promote human health and mitigate environmental impacts, especially in Western diets across high-income countries (Bonnet et al., 2020; Westhoek et al., 2014).

One way to assess the sustainability of diets is by means of Life Cycle Assessment (LCA), a standardized method to evaluate impacts from all food supply chain stages (i.e., from *cradle-to-grave*), allowing for extensions and flexibilities (Muralikrishna and Manickam, 2017; Roy et al., 2009). LCA studies emphasize the need to consider other impacts besides climate change to evaluate alternative dietary scenarios (Meier and Christen, 2013; Poore and Nemecek, 2018). Integrating nutritional aspects is particularly important in the context of agri-food systems (Heller et al., 2013; McAuliffe et al., 2020). For instance, Ribal et al. (2016) include environmental, economic, and nutritional indicators to assess the sustainability of school meals and mitigate trade-offs. Stylianou et al. (2016) combine environmental LCA with epidemiology-based nutritional indicators on human health to simultaneously evaluate environmental and health impacts of foods. Chapa et al. (2020) compare the environmental impacts of different American diets by defining alternative Functional Units (FUs) that capture the provision of nutrition and satiety as basic functions of food intake. Batlle-Bayer et al. (2020) recently proposed a FU that combines nutritional and socio-economic data to measure food affordability in LCA. Still, Life Cycle Impact Assessment (LCIA) methods often overlook human health impacts derived from food consumption, as well as further impacts on animals.

LCA could benefit from more comprehensive and integrative approaches to improve the overall sustainability of food systems at different geographical scales (Colonius and Earley, 2013; Zinsstag et al., 2011). The One Health (OH) approach can serve as an overarching framework when rethinking sustainability strategies for shaping future dietary patterns. OH is defined as "a collaborative, multi-sectoral and transdisciplinary approach to achieve optimal health outcomes recognizing the interconnection between people, animals, plants and the environment" (AVMA, 2008). As such, the OH approach can be applied to study complex health issues transecting the human-animal-environment spheres as integral parts of the food system at the local, regional, national, and global levels (Davis et al., 2017; Lebov et al., 2017). Classical OH research has mainly focused on the transmission of zoonotic pathogens in the food supply chain (Angelos et al., 2016; Klous et al., 2016). Yet, the existing link between food consumption and NCDs warrants further investigation (Afshin et al., 2019; Willett et al., 2019).

Integrating the OH domains into traditional LCA approaches is far from straightforward. LCIA methods estimate impacts of pollution and environmental degradation on human health as Disability-Adjusted Life Years (DALYs). Although several metrics related to both nutrient quantity and quality exist, the role of nutrition in LCA is commonly assessed through the definition of the FU as mass, energy or single nutrient content (Green et al., 2020; Weidema and Stylianou, 2020). Applying nutritional epidemiological concepts can help assess the relationship between dietary patterns and the risk of developing particular chronic diseases (Heller et al., 2013). Moreover, animal welfare issues are commonly disregarded in LCA and remain subject to consumers' preferences when proposing integrated sustainability actions (van der Weele et al., 2019). Only a few studies propose animal welfare indicators consistent with the LCA framework and comparable across several food items (Scherer et al., 2018, 2019).

This study aims to implement the OH approach into LCA to assess the sustainability of food consumption by considering additional indicators on human health and animal welfare from a life cycle perspective. The extended LCA framework is applied to evaluate the impacts of reference diets (RDs) for both men and women in NRW, based on data on observed food consumption at the regional level. NRW is one of the most populated areas in Europe and a typical example of Western dietary habits, i.e., characterized by high calorie and animal product intake. Alternatives to the reference NRW diets are also evaluated with the ultimate goal of providing recommendations for more sustainable dietary patterns across environmental-human-animal health dimensions.

## 2. Methods

The study departs from the LCA methodology, consisting of the following steps according to the ISO14040/44:2006 standards (ISO, 2006a, 2006b).

### 2.1. Goal and scope

The enhanced LCA is applied to the German federal state of NRW, located in the North-Western part of the country, to estimate the sustainability of the reference diet under the OH approach. With approximately 17.5 million inhabitants, NRW is one of the most populated regions in Germany, including the Rhine-Ruhr metropolitan area, the largest conurbation in Europe (Destatis, 2021b). NRW is also next to other densely populated countries in Western Europe, such as Belgium and the Netherlands (Eurostat, 2020). The FU is defined as the average food consumption per capita and day for the year 2008, based on the "National Nutrition Survey II" (NVS II) (Max Rubner Institut, 2008). Although there are more recent surveys at the national level (BMEL, 2021), the NVS II provides the most recent and representative data at the regional level, available for the federal state of NRW. Most NVS II participants were women (53.9%) with an average age of ~46 years and low physical activity level (PAL) (Max Rubner Institut, 2008). Two different mass-based FUs are considered to differentiate impacts by gender since this factor influences the predisposition to chronic diseases. Hence, the FU is estimated at 4.147 kg and 3.663 kg per capita and day for men and women, respectively. Three other dietary scenarios are examined as possible alternatives to the RD in NRW. These diets were designed by quadratic optimization to represent other consumers' choices while delivering approximately the same FUs and similar nutritional properties (see Section 2.2.1).

Impacts are quantified from *farm-to-fork* (i.e., *cradle-to-plate*). The system boundaries include the following sub-stages, as shown in Fig. 1: a) agricultural production (crop production and animal husbandry), b) transport of raw materials, c) processing into food products, d) packaging, e) distribution of food products, f) retail and g) consumption (food preparation in households, including packaging disposal). Food losses and waste are considered at the retail and consumption sub-stages. Other downstream impacts from food waste management and disposal are excluded. All sub-stages comprise the production and transportation (distribution) of the respective inputs – including energy – except for capital goods. When multiple co-products are obtained from some of the sub-stages mentioned above, partitioning is generally applied by considering their relative economic value, in line with the Product Environmental Footprint (PEF) (European Commission, 2018). The only exception is dairy production, in which physical (mass) allocation is applied among co-products of milk production (meat and feed) and processing of dairy products (skimmed milk powder, cream, milk fat derivates, etc.). Although this is not fully compliant with the PEF guidance, this follows the International Dairy Federation Guide (Broekema et al., 2019; International Dairy Federation, 2016). This also avoids the need to gather economic data for such products, for which prices are highly variable and not always available. Additionally, cut-off criteria are applied to exclude the impacts of a few co-products, namely dried citrus pulp, brewer grain,

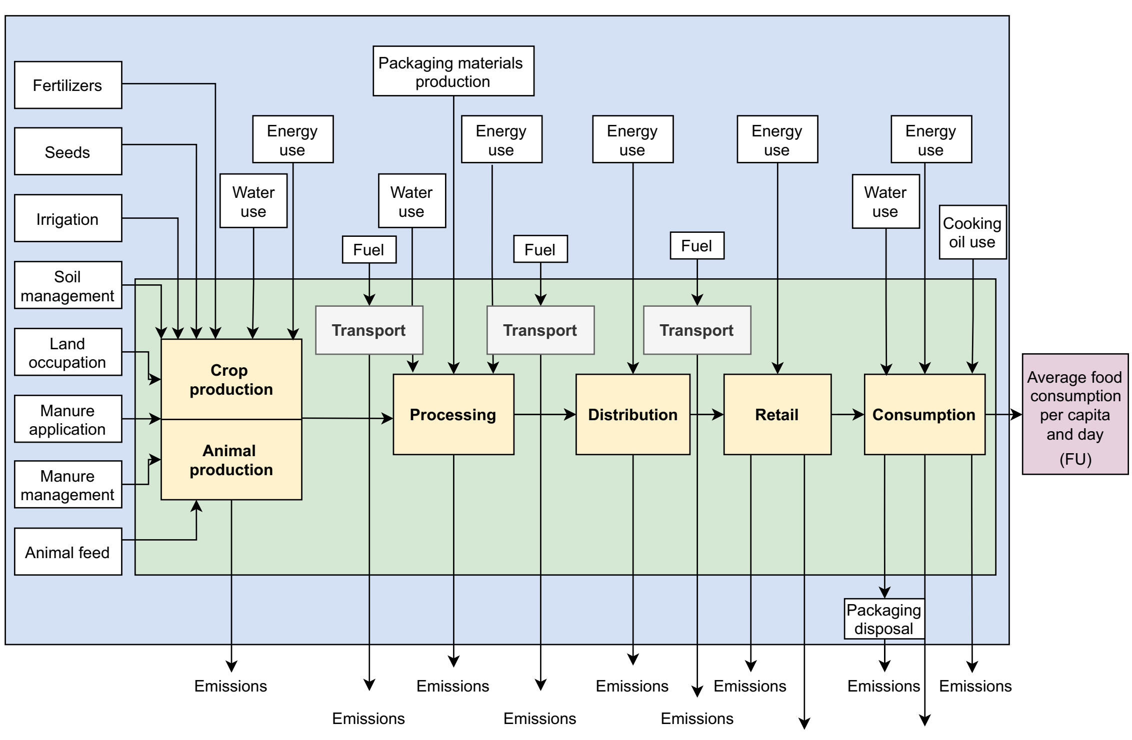


**Fig. 1.** System boundaries from farm-to-fork to estimate the impacts of reference diets of both men and women in North Rhine-Westphalia. The system includes one life cycle per food product, considering the respective quantities consumed per functional unit.

animal manure, nutshells, given their relatively low market value (Broekema et al., 2019). Agricultural production includes land use (as area occupation) but excludes land transformation (or LUC), which often implies additional $CO_2$ emissions from carbon stock changes besides other ecological alterations.

### 2.2. Life Cycle Inventory (LCI)

#### 2.2.1. Food consumption in the reference diet and alternative dietary scenarios

The quantities of each food item consumed per FU were estimated using the regional NVS II data (Max Rubner Institut, 2008). Since these data sources only provided quantities per food category, additional assumptions were needed to identify specific food items in each category and associated quantities. National-level data from Treu et al. (2017), also based on the NVS II, were used with this aim. The list of food items was further rearranged and renamed according to the product dataset in Optimeal® (Broekema et al., 2019), consistent with the EFSA Comprehensive European Food Consumption Database (EFSA, 2018a). All food items were selected by representativeness within each food category. Food items accounting for <1% of the total weight and for which no equivalent category could be identified were reallocated into the most representative or similar food item category, mainly based on the biological similarity (e.g., offal redefined as "meat products"; *sauerkraut* redefined as "head cabbage"). Only five food items were excluded, which together represent <0.0006% of the overall food consumed in 2008 (in weight) - see Tables S1 and S2 in Section S1 of the Electronic supplementary material (ESM) for further information. The two reference diets include 100 food items plus 17 beverages grouped into 16 major food categories, as shown in Table 1.

Three alternative dietary scenarios were designed to represent more recent dietary shifts in Germany, following the same approach as Kramer et al., 2017 and Tyszler et al., 2016. This consists in applying quadratic optimization in Optimeal® (Broekema et al., 2019, 2020; te Pas et al., 2021) to generate diets that are similar to the RD in terms of the overall quantities of food items consumed and associated nutritional properties; after replacing or excluding specific food items according to the consumers' choices the alternative diets aim to capture, under nutritional constraints. All food items selected were available in the EFSA dataset (EFSA, 2018a) in Optimeal®. Nutritional constraints were defined as upper and lower values for macro- and micronutrient intake in line with EFSA dietary reference values (DRV) (EFSA, 2018b, 2019), considering men and women with low PAL (1.4), same as in NVS II. Specific dietary considerations and product selection criteria applied for defining the three alternative diets are as follows:

**Table 1**
Reference diet of both men and women in North Rhine-Westphalia in grams per day.
Data source: EFSA (2018a), Max Rubner Institut (2008), and Treu et al. (2017).

| Food categories | Food items | Women | Men |
|---|---|---|---|
| Alcoholic beverages | Beer, regular | 31.20 | 175.20 |
| | Wine, red | 23.46 | 25.53 |
| | Wine, white | 10.54 | 11.47 |
| | Beer and beer-like beverages | 7.80 | 43.80 |
| | Spirits | 1.30 | 3.70 |
| | Cider | 0.99 | 1.07 |
| Animal and vegetable fats and oils | Butter | 7.85 | 12.32 |
| | Margarine, normal fat | 5.88 | 8.89 |
| | Vegetable oil | 3.27 | 4.79 |
| Ready-to-eat meals | Ready to eat soups | 71.00 | 92.00 |
| | Vegetable-based meals | 57.20 | 53.56 |
| | Prepared mixed vegetable salad | 52.80 | 49.44 |
| | Pasta, cooked | 36.00 | 47.00 |
| | Meatballs | 13.02 | 25.20 |
| | Meat-based meals | 9.92 | 19.20 |
| | Meat stew | 8.06 | 15.60 |
| | Egg-based meal | 5.00 | 4.00 |
| | Potato based dishes | 5.00 | 8.00 |
| | Pizza and pizza-like pies | 3.56 | 6.39 |
| Drinking water | Tap water | 692.79 | 710.91 |
| | Bottled water | 340.66 | 349.57 |
| | Still mineral water | 113.55 | 116.52 |
| Eggs and egg products | Chicken egg | 13.00 | 18.00 |
| Fish and other seafood | Fish products | 10.73 | 13.84 |
| | Salmon and trout | 8.44 | 9.73 |
| | Herring | 2.96 | 3.42 |
| | Shrimps | 0.87 | 1.01 |
| Fruit and fruit products | Apple | 104.49 | 93.26 |
| | Bananas | 35.78 | 29.52 |
| | Strawberries | 33.10 | 21.76 |
| | Peaches | 21.75 | 13.60 |
| | Oranges | 19.67 | 15.32 |
| | Pear | 18.44 | 16.46 |
| | Mandarins | 10.59 | 8.25 |
| | Fruit compote | 7.57 | 6.35 |
| | Kiwi | 4.88 | 4.03 |
| | Jam | 0.95 | 0.91 |
| Fruit and vegetable juices | Juice, apple | 81.12 | 92.66 |
| | Juice, orange | 69.29 | 79.14 |
| | Fruit juice | 18.59 | 21.23 |
| | Fruit and vegetable juices | 16.24 | 18.55 |
| | Fruit nectar | 9.40 | 10.74 |
| | Juice, tomato | 2.35 | 2.68 |

**Table 1** (*continued*)

| Food categories | Food items | Women | Men |
|---|---|---|---|
| Grains and grain-based products | Wheat bread and rolls | 85.12 | 112.00 |
| | Pastries and cakes | 25.60 | 36.80 |
| | Mixed wheat and rye bread and rolls | 18.62 | 24.50 |
| | Rye bread and rolls | 17.29 | 22.75 |
| | Multigrain bread and rolls | 11.97 | 15.75 |
| | Pasta, wheat flour, without eggs | 11.20 | 12.60 |
| | Cereal flakes | 9.60 | 10.80 |
| | Wheat milling products | 9.54 | 10.73 |
| | Biscuits | 1.95 | 2.81 |
| | Rice | 1.66 | 1.87 |
| Legumes, nuts and oilseeds | Tree nuts | 3.78 | 4.53 |
| | Peas, green, without pods | 3.30 | 3.57 |
| | Beans | 2.16 | 2.33 |
| | Beans, green, without pods | 1.28 | 1.39 |
| | Lentils | 1.05 | 1.14 |
| Meat and meat products | Cooked smoked sausage | 9.38 | 18.40 |
| | Chicken meat | 6.67 | 8.89 |
| | Fresh and lightly cooked sausage | 6.26 | 12.26 |
| | Pork/piglet meat | 6.23 | 13.02 |
| | Dry sausage | 5.74 | 11.24 |
| | Beef meat | 5.56 | 11.64 |
| | Sausages | 4.69 | 9.20 |
| | Mixed beef and pork meat | 4.42 | 7.32 |
| | Turkey meat | 1.18 | 1.57 |
| | Veal meat | 0.79 | 1.66 |
| | Ham, pork | 0.74 | 0.71 |
| | Meat and meat products | 0.60 | 0.74 |
| | Mutton/lamb meat | 0.56 | 1.16 |
| | Bacon | 0.20 | 0.19 |
| Milk and dairy products | Cow milk | 101.65 | 126.12 |
| | Yogurt, cow milk, plain | 42.20 | 37.19 |
| | Fermented milk products | 30.14 | 26.57 |
| | Quark | 14.70 | 15.38 |
| | Cheese | 14.15 | 14.81 |
| | Buttermilk | 13.78 | 12.14 |
| | Cheese, Gouda | 7.08 | 7.41 |
| | Flavored milk | 6.35 | 7.88 |
| | Cheese, Edam | 3.27 | 3.42 |
| | Evaporated milk | 2.40 | 2.58 |
| | Cheese, Camembert | 2.18 | 2.28 |
| | Cheese, processed spreadable | 1.63 | 1.71 |
| | Cream | 0.48 | 0.52 |
| Non-alcoholic beverages | Coffee | 552.00 | 628.00 |
| | Herbal tea, infusion | 209.44 | 99.33 |
| | Black tea, infusion | 62.56 | 29.67 |
| | Soft drink, flavored | 42.32 | 107.64 |
| | Cola beverages, caffeine | 27.60 | 70.20 |
| | Soft drink, fruit content | 22.78 | 57.46 |
| Snacks, desserts, and other foods | Starchy pudding | 22.38 | 23.03 |
| | Ice cream, milk-based | 10.40 | 12.40 |
| | Custard | 6.50 | 7.75 |
| | Ices and desserts | 5.72 | 6.82 |
| | Snack food | 5.28 | 7.92 |
| | Pretzels | 0.72 | 1.08 |
| Starchy roots and tubers | Potato boiled | 36.92 | 46.80 |
| | Potatoes and potatoes products | 17.75 | 22.50 |
| | French fries | 9.23 | 11.70 |
| | Main-crop potatoes | 7.10 | 9.00 |
| Sugar and confectionary | Chocolate (Cocoa) products | 8.65 | 8.65 |
| | White sugar | 8.48 | 8.48 |
| | Confectionery (non-chocolate) | 4.75 | 4.75 |
| | Molasses and other syrups | 1.85 | 1.85 |
| | Honey | 1.28 | 1.28 |
| Vegetables and vegetable products | Carrots | 24.96 | 21.09 |
| | Tomatoes | 23.86 | 19.06 |
| | Head cabbage | 13.51 | 12.19 |
| | Tomato purée | 11.43 | 10.78 |
| | Leafy vegetables | 9.87 | 8.91 |
| | Cucumbers | 9.77 | 7.97 |
| | Leek | 5.20 | 4.69 |
| | Onions, bulb | 5.20 | 5.63 |
| | Peppers, paprika | 4.30 | 3.44 |
| | Spinach (fresh) | 2.08 | 1.88 |
| | Cultivated mushroom | 1.04 | 0.94 |
| Total | | 3663 | 4147 |

a. ***German Nutrition Society (DGE) diet (DD)***: this diet is designed according to the official dietary recommendations of the DGE for daily intake within seven food groups following a descending orientation circle (DGE, 2021). The DD represents a health-oriented and nutritionally-balanced food selection, primarily based on whole foods, minimizing ultra-processed foods, and including almost three times the amount of vegetables as the RD.
b. ***Vegan diet (VD)***: this is a 100% plant-based diet, excluding all animal-based products (e.g., meat, dairy, eggs, fish, and honey), following recommendations of the DGE (Richter et al., 2016). Due to the many dietary constraints applied, only tolerable upper nutrient intake levels (EFSA, 2018b) were considered as nutrient constraints to avoid adverse health risks. At the product level, plant-based food items replace milk and dairy, meat products, and eggs. In particular, the consumption of grains, nuts, legumes and pulses is substantially increased relative to RD.
c. ***Mediterranean diet (MD)***: This diet is characterized by a high intake of plant-based and fish products, according to the pyramid and meal plan from Bach-Faig et al. (2011) and Fidanza and Alberti (2005). The MD entails a significant increase in consumption of fruits and vegetables relative to RD, and three times the amount of fish. Food items were selected to represent a preference for regional products, based on statistics of overall food supply in NRW (IT.NRW, 2020; Verbraucherzentrale NRW, 2015) and food imports at the country level (Eurostat, 2021; FAOSTAT, 2021). Yet, a large share of this diet (~38%) is covered by imports, i.e., fish, nuts and seeds, olive oil, fruit s and vegetables and wine.

The quadratic optimization yields approximately the same amount of overall food consumed (kg per capita and day) as in the RD, in order to have comparable FUs for both men and women, respectively: 3.787 and 3.897 kg in the DD; 4.029 and 4.207 kg in the VD; and 3.536 and 3.399 kg in the MD. More specific information on the food items, quantities consumed and nutritional properties per day of the alternative dietary scenarios can be found in Section S1 (Tables S3 and S4) and Section S4 (Tables S13 and S14). As a result of the optimization, the above-described diets provide between 1800 and 1830 kcal per day for women and between 2230 and 2280 kcal for men, which are slightly less kcal than in the RD – i.e., 1999 and 2643 kcal per person and day, for women and men, respectively. The optimized diets are still in line with the dietary reference values for EU adults with low physical activity, i.e., between 1800 and 1820 kcal for women and between 2230 and 2280 kcal for men. Uncertainty analysis of the aforementioned scenarios was conducted through 100-run Monte Carlo simulations in Optimeal® to assess variability in each diet's composition (in terms of quantities of the respective food items consumed), associated nutrients, and impacts resulting from the optimization.

#### *2.2.2. LCI of the respective food products*

The software Optimeal® (Broekema et al., 2019) and its underlying dataset were used to estimate aggregated impact values per 100 g of food product along its life cycle, i.e., from *cradle-to-plate*. Impacts were estimated by multiplying impact values and the respective quantities consumed of each food item per FU (see Fig. 1). Optimeal® follows the methodological recommendations of the PEF Guidance 6.3 in terms of the LCI from *processing-to-mouth* for various products (European Commission, 2018). This refers to energy use, water consumption, food losses and cooking methods (Broekema et al., 2019). There are few exceptions as for the dairy production processes. LCI modeling in Optimeal® is carried out with SimaPro, based on specific data sources and methodological assumptions, as detailed below (see Section S2 of the ESM for further details):

a. ***Agricultural production***: Optimeal® determines agricultural production's origin by considering an average mix of major producer/exporter countries and associated shares, based on FAOSTAT data for the period 2009–2013 (FAOSTAT, 2013) combined with additional trade statistics (Broekema et al., 2019). Impacts from crop production arise from land occupation, soil management, irrigation, manure application, seeds, fertilizers and energy and water consumption in agricultural operations; excluding pesticides the LCI data of which is not available for all food products in the analyzed diets. Livestock production includes impacts from animal feed, as well as emissions from enteric fermentation and manure management (Broekema et al., 2019). Emissions to air, soil and water are modeled considering the characteristics of each production system. Cultivation of crops (also animal feed) uses country-level data for major sourcing regions. As for animal farming, most processes are modeled based on regional data that is representative of intensive production systems in Western Europe (mainly the Netherlands and Ireland), i.e., dairy, pig, poultry (i.e., eggs and broiler) and beef farms (Durlinger et al., 2017a). Other animal production systems, i.e., fisheries, aquaculture, and beekeeping, also include the production of materials, energy, fish meals, and the management of beehives (Arena et al., 2014; Broekema et al., 2015). LCI data is estimated according to the Agri-footprint 4.0 methodology – compliant with the PEF guidance – as regards allocation and the calculation of emissions from crop management and animal production (Durlinger et al., 2017b). Food losses from agricultural production are however not considered.
b. ***Transport of raw materials***: Transport of outputs and inputs across sub-stages is included by assuming the average distance of travel per mean of transport (road, rail, water, air), the relative tonnage load capacity of the vehicles used, and their respective load factor, type of fuel, and emission intensity, according to the Agri-footprint 4.0 method (Durlinger et al., 2017a).
c. ***Processing into food products***: Optimeal® includes milling, parboiling, extraction, refining, and meat processing using the Agri-footprint 4.0 method (Durlinger et al., 2017a). Energy and water consumption is estimated according to the PEF Guidance (European Commission, 2018). Additional data sources used for other specific processes are described in Table S5 in ESM.
d. ***Packaging***: The production of packaging materials is included using the Ecoinvent 3.4 database (Wernet et al., 2016), which comprises the most common food packaging materials. Only aluminum production is modeled based on the ELCD database (JCR-IES, 2012). Transport of packaging materials is included by considering the average distance covered by truck, ship, and train, based on the PEF Guidance (European Commission, 2018).
e. ***Distribution of food products***: Cooling, freezing, lighting, and heating are included, considering the storage time and product density, according to the PEF Guidance (European Commission, 2018).
f. ***Retail***: Retail activities are modeled by taking default parameters from the PEF Guidance (European Commission, 2018). This includes energy use during retail storage (i.e., cooling, freezing, and lighting, excluding heating), food losses at the retail facility, travel distances and means of transport.
g. ***Consumption***: Optimeal® estimates energy use for cooking, frying, boiling, baking, microwaving, cooling, and freezing, considering the time of preparation per food product and a *raw-to-cooked ratio*. Production of additional inputs (e.g., oil for frying, water for brewing) and food losses at the household are calculated based on the PEF Guidance (European Commission, 2018). Consumption also includes disposal of food packaging according to Ecoinvent 3.4 (Wernet et al., 2016), assuming average disposal scenarios in the European context (see Table S5 in the ESM).

### *2.3. Life cycle impact assessment (LCIA)*

The LCIA considers environmental impact indicators at the midpoint level, and human health and animal welfare loss as additional indicators. It must be noted that animal welfare impacts are associated with the production of animals up to the processing sub-stage, i.e., from animal husbandry to slaughtering; from aquaculture/fisheries to cleaning/degutting; and from beehive management to honey extraction. The impacts on human health are generated only through food consumption (see Fig. 1).

*2.3.1. Environmental impact indicators*

The environmental dimension is assessed through the ReCiPe 2016 characterization method (Huijbregts et al., 2017) at the midpoint level, to provide detail on the sources of environmental degradation. Specifically, the following impact categories are considered: a) climate change (as kg $CO_2$-eq), b) fine particulate matter (as kg $PM_{2.5}$-eq), c) terrestrial acidification (as kg $SO_2$-eq), d) freshwater eutrophication (as kg P-eq), e) marine eutrophication (as kg N-eq), f) land occupation (as $m^2$ of crop equivalent), g) fossil resource scarcity (as kg oil-eq) and h) water use (as $m^3$). These include the most relevant impact categories as identified by the PEF Guidance (European Commission, 2018). The same LCIA methods are applied regardless of the country of origin of the products consumed, as these are defined globally. It should be noted that toxicity-related impacts are excluded, as the estimation of these impacts requires quantifying emissions arising from the pesticide use, excluded from the LCI due to data limitations. This is in line with the goal of the study, which is to estimate human health impacts associated with dietary risk factors for NCDs.

*2.3.2. Animal welfare indicators*

Animal welfare indicators are defined according to the methodology proposed by Scherer et al. (2018), which covers the impacts from farm to slaughter. Specifically, three indicators are considered to assess animal welfare loss, expressed in a) “Animal Life Years Suffered (ALYS)”, b) “loss of Animal Lives (AL)” and c) “loss of Morally-Adjusted Animal Lives (MAL)”. These correspond to midpoint-level indicators and are quantified by applying the equations below (Eqs. (1)–(7)).

$$ALYS = NAf \times [(Ld - Sd) \times (1 - Q) + Sd] \quad (1)$$

$$AL = LL + LD \quad (2)$$

$$MAL = NAf \times (1 - Lf) \times mv \quad (3)$$

$$NAf = \frac{1}{(Lw \times Pf)} \quad (4)$$

$$LL = NAf \times (1 - Lf) \quad (5)$$

$$LD = NAf \times [(Lf - Sf) \times (1 - Q)] + Sf \quad (6)$$

$$Lf = \frac{Ld}{L_{exp}}; Sf = \frac{Sd}{L_{exp}} \quad (7)$$

where: NAf: “number of animals affected”; Q: “quality of life”; Ld: “life duration”; Sd: “slaughter duration”; LL: “lives lost”; LD: “lives with disability”; Lf: “life fraction”; Sf: “slaughtering fraction”; $L_{exp}$: “life expectancy”; mv: “moral value”; Lw: “live weight”; Pf: “food product fraction”. Source: Scherer et al. (2018).

ALYS measures the loss of life quality due to farm conditions, defined by the space allowance (or stocking density) throughout the animal lifetime, for the different animal husbandry systems (e.g., cattle, swine, poultry, fish and shrimp aquaculture, beekeeping). *Quality of life* is calculated differently for each animal, following regression equations retrieved from Scherer et al. (2018) and adapted to the standards or minimum requirements established by official German animal welfare protection laws (see Table S6 in Section S3). The *number of animals affected* considers the number of animals involved in the FU and is given by the *food product fraction*, defined as the ratio of the average slaughter yield (in kg/animal) to the live animal weight (kg/animal).

AL measures the number of *lives lost* (LL) and *lives with disability* (LD), similar to human DALYs. The indicator considers the premature death imposed on animals through slaughtering due to production purposes; and the distress caused during their farm life and slaughter, measured as time fractions of suffering through a lifetime. Both life and slaughter fractions are calculated in relation to the animal's life expectancy and the respective durations in years. The slaughter fraction entails catching animals at the farm, transporting them to the slaughterhouse and keeping them until the moment of their death. For dairy cows, the time suffered through milking during their entire lifetime is also taken into account. The ESM describes the LCI data sources, assumptions and calculations for each criterion in detail (see Table S7 in Section S3).

MAL measures the degree of animal awareness by establishing a *moral value* (mv), which depends on the animal's self-awareness and intelligence based on the neuron count and brain mass. This captures each animal's intrinsic value, based on its sense of awareness and emotions related to its experiences (Phillips and Kluss, 2018). The *mv* is calculated by dividing the animals' biological values by the corresponding human's value (Scherer et al., 2018). When available, the *mv* includes the number of cortical neurons and the total number of neurons to predict intelligence between species, as suggested by Herculano-Houzel (2012). Since data are not always available, the *encephalization quotient* (EQ) was additionally taken into account, often used as a proxy to compare intelligence across species, considering the *brain-to-body weight ratio* (Jerison, 1975) as shown in Eqs. (8)–(9). Further information related to calculation steps and assumptions can be found in the ESM (Table S8 in Section S3).

$$EQ = brain\ weight \times \left(0.12 \times body\ weight^{0.67}\right) \quad (8)$$

$$mv = [(CNa/CNh) + (TNa/TNh) + (EQa/EQh)]/3 \quad (9)$$

where: CNa: animal number of cortical neurons; CNh: human number of cortical neurons; TNa: animal total number of neurons; TNh: human total number of neurons; EQa: animal encephalization quotient; EQh: human encephalization quotient. Source: Jerison (1975) and Scherer et al. (2018).

After deriving ALYS, AL, and MAL values per gram of animal product, these were used as input for calculating impacts derived from processed food items, such as baked products or meat and dairy products, and more sophisticated food preparations at the household level. Major data sources and assumptions for this conversion and associated intermediate impact values are detailed in Section S3 of the ESM (Table S9). “Other meat” refers to meat not elsewhere classified, i.e., veal, mutton and lamb. It was assumed that these animals have similar welfare conditions as sheep due to lack of data (Scherer et al., 2019).

*2.3.3. Human health indicators*

Human health indicators are based on nutritional quality indices using epidemiological studies as proposed by Heller et al. (2013). These comprise a framework for health assessment on a diet level integrated into LCA by relating risk factors to underlying causes of death. The link between food intake in the LCI data and dietary risk factors was established in the same way as Stylianou et al. (2016). Epidemiological data from the Global Burden of Disease (GBD) database were used as characterization factors for human health impact at the endpoint level expressed as DALYs – years of life lost due to death or disability caused by a disease (Kirch, 2008). The GBD database provides country-level DALY values related to 15 dietary risk factors for several diseases, by gender (GBD 2019, 2020).

NCDs were assessed as indicators of human health. Drawing from the GDB database (GBD 2019, 2020), DALYs associated with each selected NCD by gender were estimated for Germany in the year 2019. Each DALY represents one healthy year of life lost due to death or disability. In this study, only DALYs attributed to dietary risk factors were considered to represent the disease burden associated with dietary choices. The extracted data was filtered so that only risk factors that

**Table 2**
Dietary risk factor exposure, optimal levels of daily intake and daily intake values in reference diets of both men and women in North Rhine-Westphalia.

| Dietary risk factor exposure | Optimal level of daily intake | Reference diet daily intake values | |
|---|---|---|---|
| | | Women | Men |
| Diet high in processed meat (g/day) | <0 g/day | 27.00 (−) | 52.00 (−) |
| Diet high in red meat (g/day) | <16.2 g/day | 49.15 (−) | 95.55 (−) |
| Diet high in sodium (mg/day) | <1000 mg | 2608.73 (−) | 3369.30 (−) |
| Diet high in sugar-sweetened beverages (kcal) | <50 kcal | 38.12 (+) | 89.91 (−) |
| Diet high in trans-fatty-acids (%E) | <0.5% | 0.71 (−) | 0.75 (−) |
| Diet low in polyunsaturated fatty acid (PUFA) (%E) | >12% | 6.13 (−) | 6.12 (−) |
| Diet low in seafood omega-3 fatty acids (mg/day) | >250 mg | 708.68 (+) | 841.18 (+) |
| Diet low in vegetables (g/day) | >397 g/day | 111.22 (−) | 96.57 (−) |
| Diet low in legumes (g/day) | >50 g/day | 7.79 (−) | 8.44 (−) |
| Diet low in fruits (g/day) | >312 g/day | 257.22 (−) | 209.46 (−) |
| Diet low in whole grains (g/day) | >113.4 g/day | 57.48 (−) | 73.80 (−) |
| Diet low in fiber (g/day) | >30 g/day | 24.51 (−) | 27.46 (−) |
| Diet low in nuts and seeds (g/day) | >16.2 g/day | 3.78 (−) | 4.53 (−) |
| Diet low in calcium (mg/day) | >1200 mg | 945.10 (−) | 1073.91 (−) |
| Diet low in milk (g/day) | >490 g/day | 108.00 (−) | 134.00 (−) |

Note: Symbols (−) indicate the reference diet intake values are not within the optimal levels of intake, and constitute a factor of risk exposure. Symbols (+) indicate the reference diet intake values are within the optimal levels of intake, not constituting a factor for risk exposure (Afshin et al., 2019; GBD 2019, 2020).

contribute >5% to the total disease burden of the particular disease were included. As a result, the following NCDs were selected to indicate the human health impact of diet: a) cardiovascular diseases (ischemic heart disease and hypertensive heart disease); b) diabetes and kidney diseases (including diabetes mellitus type I and II); c) stroke and d) neoplasms (including colon, rectum, stomach, esophageal and breast cancers).

Nutrients contained in the respective food products in Optimeal® are based on the European Food Composition Database (EFSA, 2019). These data comprise 60 nutrients in total, including macronutrients and micronutrients, e.g., fiber and vitamin A, for over 2500 food products, considering multiple preparation methods commonly applied in ten European countries (Broekema et al., 2019). Nutritional indices derived from food items consumed within the diets were qualified as dietary risk factor exposure to estimate the underlying diseases affecting human health, using optimal levels of intake available in the GBD database. The optimal intake level and the reference diet intake values for both men and women are shown in Table 2 (see Table S10 in the ESM for further details).

## 3. Results

### 3.1. Impact results from the reference diets in NRW

The overall impacts resulting from the RD in NRW relate to the quantity of food consumed and the underlying food product choices. Men's diet shows higher impact values than women's because of the greater quantity of food consumed per FU and the larger share of high-impact food items. Notably, men consume 98 g/day of animal protein (i.e., meat and sausages), almost twice the amount observed in the women's RD (53 g/day). Moreover, men's consumption of beverages is relatively higher than women's, e.g., men consume almost six times the amount of beer (and similar alcoholic beverages) consumed by women and 2.5 times the amount of sweetened soft drinks. In contrast, women consume milk and dairy and fruits and vegetables in much larger amounts than men, i.e., respectively accounting for 7% and 10% of the total food consumed vs. 6% and 7% in men's RD. Both men and women consume coffee in large amounts, accounting for around 15% of their diet in weight. Total animal-based or animal-containing products represent around 10–12% of the FU in both RDs while contributing to 27–29% of total energy intake in kcal. As described below, these products are major contributors to environmental impacts, animal welfare loss and human health impacts.

Environmental impacts per FU are shown in Fig. 2. Animal-based products (e.g., beef, sausages), ready-to-eat meals (e.g., soups) and other meat-based dishes (e.g., meatballs, meat stew) are among the five most common food items in both RDs. *Meat and meat products* and *ready-to-eat meals* make the greatest contribution to all environmental impacts considered. For instance, *meat and meat products* account for 22% and 29% of the climate change impact from both men and women's RDs, respectively; while *ready-to-eat meals* account for 24% and 26% of them (Fig. 2a). Similarly, meat products account for >24% and >32% of the following impacts in women and men's RDs, respectively: fine particulate matter formation (Fig. 2b), terrestrial acidification (Fig. 2c), freshwater eutrophication (Fig. 2d), marine eutrophication (Fig. 2e) and land occupation (Fig. 2f). This is due to the animal feed production impacts in major exporting countries (mainly the United Kingdom, the United States, Brazil, India, and Pakistan) to supply intensive livestock systems (Durlinger et al., 2017a). After *ready-to-eat meals* and *meat and meat products*, the consumption of *fruit and fruit products* and *fruit and vegetable juices* is a significant cause of water use (Fig. 2g). Especially in women's diet, these product categories account for around 20% and 11% of the impact, respectively. Similarly, *milk and dairy products* account for between 14% and 18% of all environmental impacts in women's diet, compared to between 8% and 13% in men's diet. *Ready-to-eat meals, meat and meat products*, and beverages (e.g., bottled water and beer) are also important contributors to fossil resource scarcity in both diets, mainly due to energy and raw materials consumption and packaging production, respectively (Fig. 2h). Coffee consumption mainly influences water use, land use and climate change.

As for animal welfare, men's RD performs worse than women's due to their overall preferences for animal-based products. The products with the highest animal welfare loss intensity are *sugary and confectionery goods* and *fish and seafood*, as shown in Fig. 3. This can be explained by the number of individuals affected per unit of product, e.g., 485 bees/kg of honey, 52.2 shrimps/kg of seafood or 2.2 fishes/kg of fish, as compared to 0.004 cows/kg of beef, 0.0092 pigs/kg of pork or 0.52 chickens/kg of chicken (see NAf in Eqs. (1) to (3) and Tables S11 and S12 in the ESM). *Fish and seafood* – including shrimps, herring and salmon – account for around 81% of the ALYS in both RDs (Fig. 3a). Sugary foods – including honey and candies with gelatine content – are associated with 76% and 81% of total AL losses (Fig. 3b); and 54% and 62% of MAL losses (Fig. 3c) in men and women's diets, respectively. *Meat and meat products* still make a significant contribution to MAL, accounting for 37% and 30% of it in men and women's diets, respectively (Fig. 3c). This food group also represents between 5% and 10% of the estimated value of ALYS and AL (Fig. 3a, b) related to the consumption of other meat and poultry. *Milk and dairy products* and *chicken eggs* play a minor role in both ALYS and AL (Fig. 3a, b).

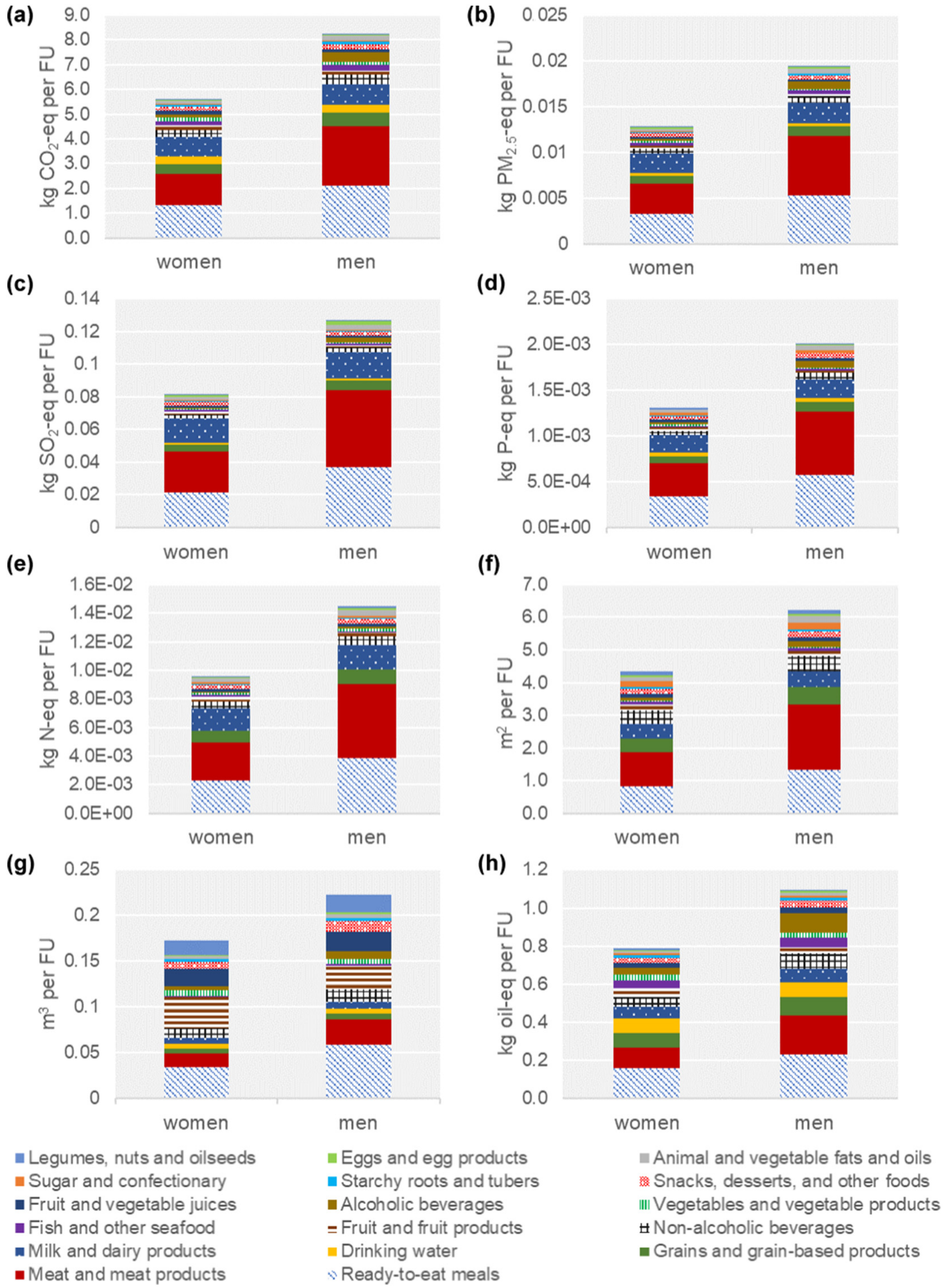


**Fig. 2.** Environmental impacts of reference diets of both men and women in North Rhine-Westphalia per functional unit: (a) climate change; (b) fine particulate matter formation; (c) terrestrial acidification; (d) freshwater eutrophication; (e) marine eutrophication; (f) land occupation; (g) water use; (h) fossil resource scarcity.

Human health impacts are shown in Fig. 4 as DALYs broken down by dietary risk factors across several NCDs, by gender. The men's RD is associated with higher DALYs across the considered NCDs, except for esophageal and breast cancers. None of the RDs falls entirely within the optimal levels of intake (see Table 2). Only the intake of omega-3 (in both RDs) and of sweetened beverages (in women's) is in line with the optimal levels. As a result, the observed unbalanced diets pose a health risk of developing chronic diseases. DALYs attributable to dietary risk factors are gender-dependent and based on epidemiological studies; thus, significant differences between both RDs can be observed. Dietary risk factors exposure per FU is higher in men than in women and delivers a greater loss of potential healthy years. The prevalent NCDs in both men and women's diets are cardiovascular diseases, specially ischemic heart disease. A large proportion of DALYs arises from the low intake of legumes and whole grains and the high intake of sodium and trans fatty acids. The latter is mainly associated with the consumption of bread and butter/margarine, pastries, ready-to-eat meals and processed meat (i.e. sausages). Specifically, dietary risk factors pose health

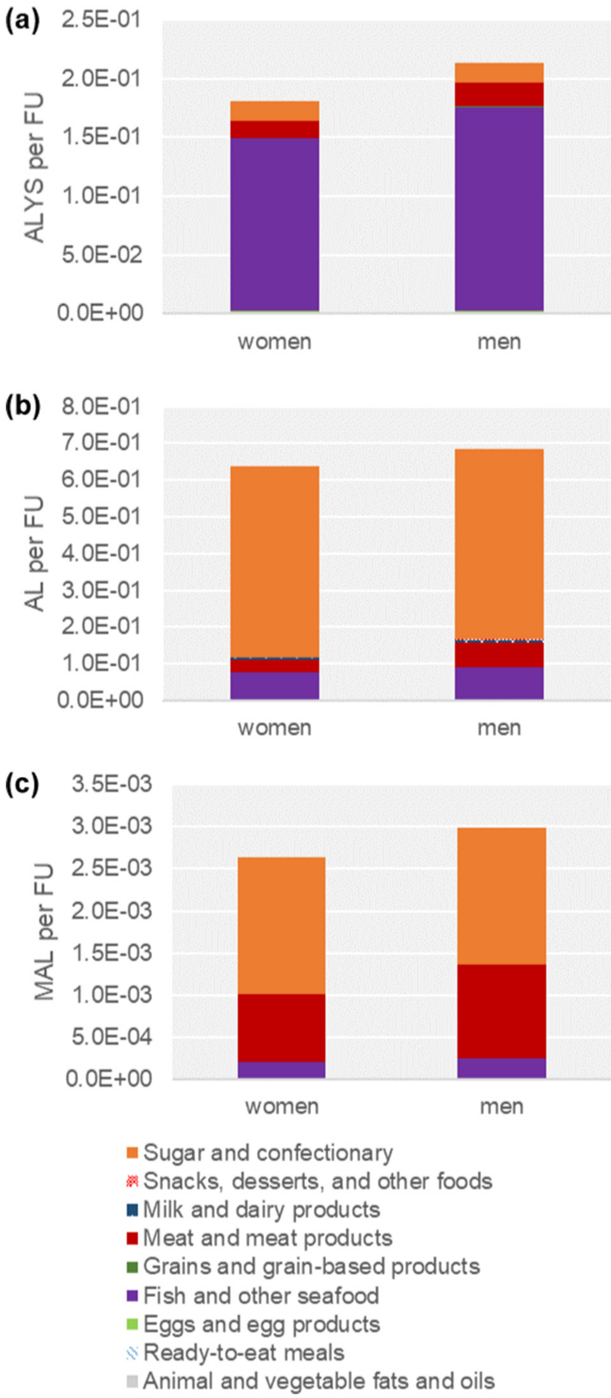


**Fig. 3.** Impacts on animal welfare of reference diets of both men and women in North Rhine-Westphalia per functional unit: (a) Animal Life Years Suffered (ALYS); (b) loss of Animal Lives (AL); (c) loss of Morally-adjusted Animal Lives (MAL). Note that *grain-based products* include pasta and baked products, which may contain animal-based ingredients (e.g., eggs, butter, milk).

risks of 0.802 and 0.666 DALYs for ischemic heart diseases for men and women, respectively; while 0.503 and 0.348 DALYs are linked to all cardiovascular diseases. Likewise, the total burden of diabetes type I and type II (higher in men's diet) ranges between 0.271 and 0.463 DALYs for both genders, attributed to the high intake of processed meat and red meat. Stroke is associated with >0.25 DALYs due to the high intake of red meat and sodium in both RDs. DALYs related to colon and rectum cancer are also significant for both genders (between 0.438 and 0.464), mainly due to the low intake of whole grains and milk.

### 3.2. Impact results from alternative dietary scenarios

As shown in Fig. 5, all alternative dietary scenarios decrease most environmental impacts relative to the RD in NRW – see Table S16 in Section S4 of the ESM for further details. For instance, both DD and MD decrease the climate change impact by around 20–30%, while the impact is >50% lower in the VD (Fig. 5a). Other impacts such as terrestrial acidification (Fig. 5c), freshwater eutrophication (Fig. 5d), marine eutrophication (Fig. 5e), land occupation (Fig. 5f) and fossil resource scarcity (Fig. 5g) also decrease significantly. This is mainly due to the reduced consumption of *ready-to-eat meals*, *meat and meat products* in the alternative diets relative to RD; combined with the increased consumption of *vegetables*, *grains and gran-based products*, *legumes, nuts and seeds* (see Section 4.1). However, trade-offs arise for other environmental impacts such as water use, which is 28% and 80% greater in the MD and VD, respectively (Fig. 5h). This is due to the higher consumption of *legumes, nuts, seeds* (e.g., almonds, nuts, hazelnuts), *fruits* (e.g., strawberries and peaches), and *vegetable fats and oils* (e.g., olive oil) in both diets.

Trade-offs are also observed among animal welfare indicators. For instance, DD and MD lead to a reduction in AL of around 17%-21% in men's dietary scenarios and of >80% in women's (Fig. 5 j). A reduction of between 30% and 70% in MAL is also observed in both men and women's alternative dietary scenarios (Fig. 5k), due to the reduction of sugary and confectionery foods consumption (which use honey and gelatin). On the contrary, the MD implies a more than three-fold increase in ALYS in men's scenarios, relative to RD, due to the substantial fish intake; while DD decreases ALYS by only 1% (Fig. 5i). It must be noted that the optimization to define alternative dietary scenarios generated minor changes in food consumption quantities in DD compared to RD (see Table S4 in ESM). In contrast, the men's MD requires much larger quantities of fish and seafood – i.e., shrimps, salmon and trout and herring – to meet the dietary and nutritional constraints applied (see Section 2.2.1). In the case of women, the MD only entails a moderate increase in fish products consumption relative to RD, combined with a decreased honey intake (see Table S4 in the ESM). This is why all optimized scenarios for women's diet deliver substantial impact savings across animal welfare indicators, especially for AL and MAL. The relatively wider variability in ALYS, AL and MAL in the MD of men is indeed due to the estimated variability in consumption of fish products to meet the optimization criteria.

The three alternative dietary scenarios also yield reduced impacts on human health, translating into health benefits (Fig. 5l) – see Table S15 in Section S4 for disaggregated impact results across NCDs. All alternative diets significantly decrease DALYs (between 27% and 73%) linked to several NCDs, namely cardiovascular diseases, ischemic heart disease, stroke, colon and rectum cancer, diabetes type II. VD causes the lowest exposure to dietary risk factors and hence the smallest impact among all diets. However, there is still the risk of developing hypertensive heart disease and stomach cancer in both men and women due to the high intake of sodium observed in VD as well as in DD and MD. DD and MD also show a significant contribution to total DALYs for diabetes type I and II, and colon and rectum cancer; this is greater than in VD due to the higher intake of red and processed meat, and the lower intake of calcium. The DD, considered a national reference for a healthy diet, constitutes a decrease of around 30% in most NCDs relative to the RD in NRW. However, DD causes a higher impact on human health than MD and VD, mainly because the selection of products is more similar to RD than in the other two alternative scenarios; but also because the intake of fruits, vegetables and whole grains is still below optimal levels, despite increases. The variability in human health impact results is relatively wider than in the other OH dimensions (Fig. 5l). This is due to the variability in the nutrients consumed per diet – within the established range –, since DALYs are very sensitive to nutrient excess or deficiency in relation to recommended quantities (see Tables S13 and S14).

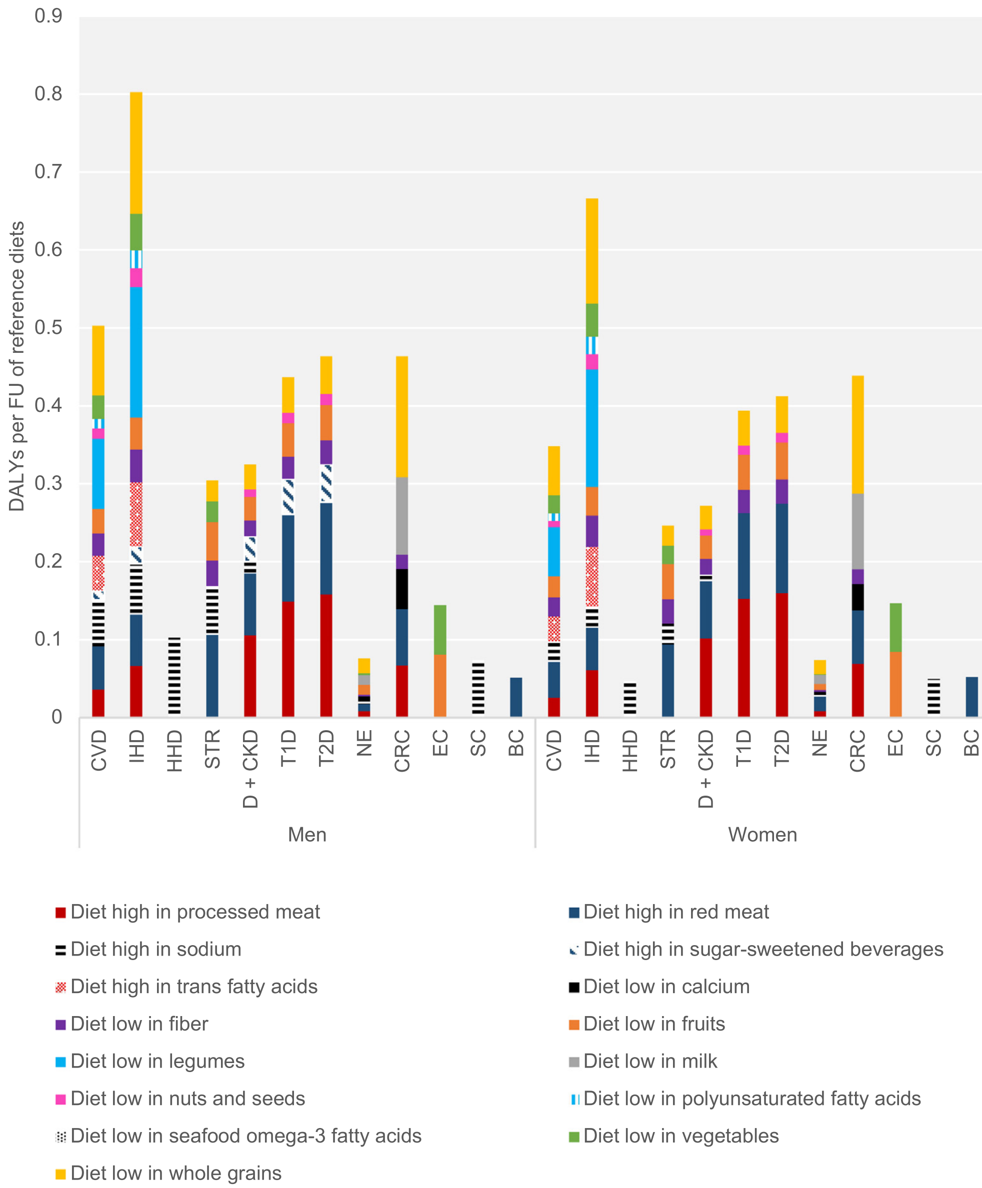


**Fig. 4.** Impacts on human health as Disability-Adjusted Life Years (DALYs) caused by several non-communicable diseases (NCDs) attributed to dietary risk factors by gender, due to reference diets of both men and women in North Rhine-Westphalia. CVD: cardiovascular diseases; IHD: ischemic heart disease; HHI: hypertensive heart disease; STR: stroke; D + CKD: diabetes and chronic kidney diseases; T1D: type I diabetes; T2D: type II diabetes; NE: neoplasms; CRC: colon and rectum cancer; SC: stomach cancer; EC: esophageal cancer; BC: breast cancer; TBLC: tracheal, bronchial, and lung cancer.

## 4. Discussion

### 4.1. Sustainability assessment under the OH approach

This study expands the traditional LCA framework with quantitative indicators on animal welfare and human health to measure the sustainability of Western diets and potential improvements driven by dietary shifts considering all dimensions of the OH concept. The application of the framework to the case study of NRW shows that shifting to any of the assessed alternative scenarios (DD, MD and VD) would yield improvements in most indicators assessed, although a few trade-offs arise, i.e., greater water consumption in VD and MD or higher ALYS in MD, relative to RDs. This is mainly due to changes in the diet composition (or *basket of products*), which also leads to slightly smaller amounts of total food consumed and fewer calories in the alternative dietary scenarios than in the RD. This implies that following the recommendations for a healthy and balanced diet – according to EFSA dietary reference values (EFSA, 2019) – can also translate into environmental benefits. Evaluating FUs other than mass-based (e.g., energy- or nutrition-based) could provide a complementary standpoint on the sustainability of dietary shifts (Green et al., 2020; McAuliffe et al., 2020). Although it is not clear if the actual biological function of food is fully represented in energy- or mass-based FUs, this study takes a similar approach to that applied by the European Commission (i.e., based on the basket of products at the country-level), which works as a compromise solution to assess large food consumption systems (Castellani et al., 2019; Notarnicola et al., 2017b; Sala et al., 2019b). However, this approach for the FU definition entails challenging issues such as how to capture the nutrition provision of food or other essential cultural and social values (Notarnicola et al., 2017a; Sala et al., 2019a, 2019b). Besides the nutritional quality, sustainable diets should reckon socio-economic dimensions of food consumption and food product (un)affordability for socially disadvantaged groups (Batlle-Bayer et al., 2020). In the case of NRW diets – mainly capturing middle or upper classes, women were relatively socially disadvantaged in employment status and income within the population considered for the nutrition survey (Max Rubner Institut, 2008).

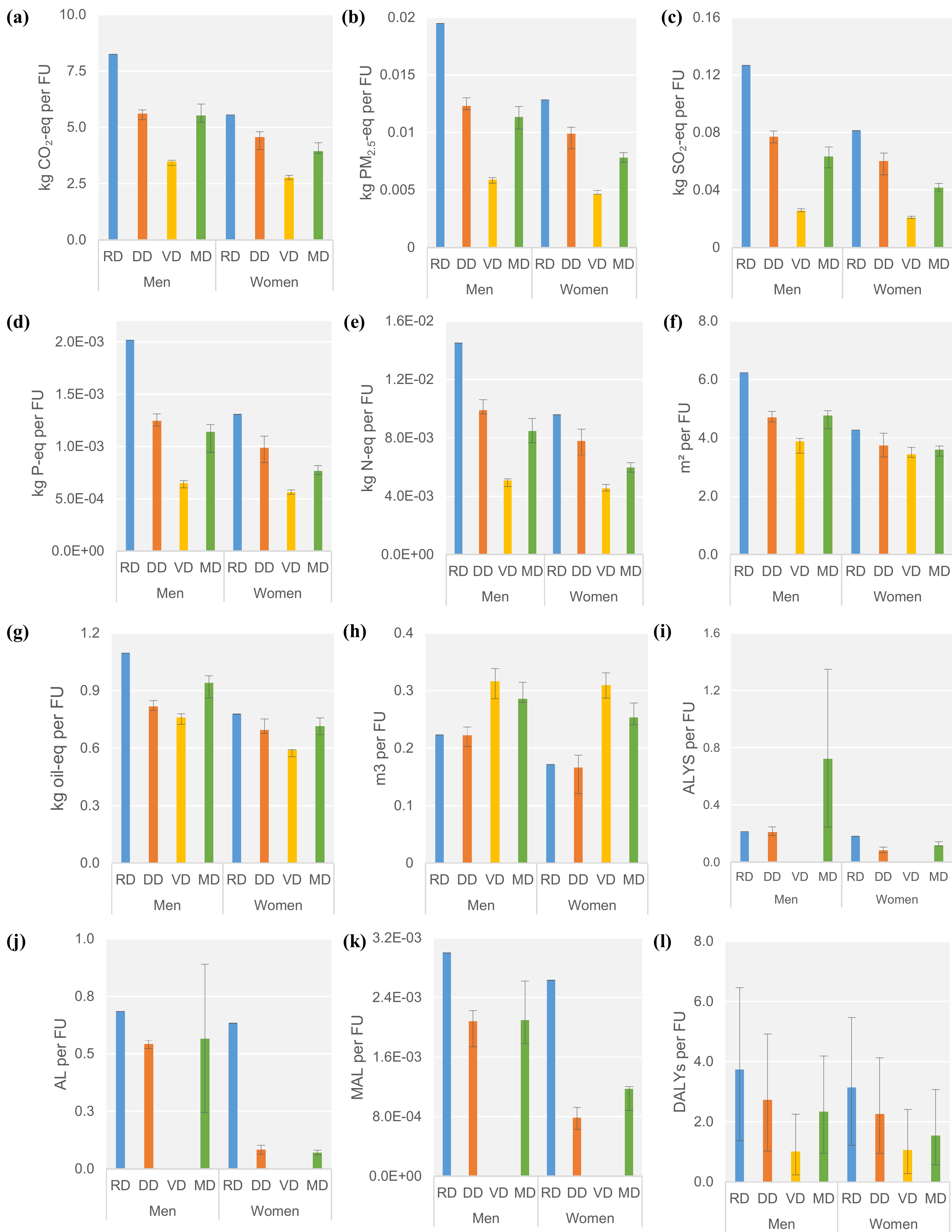


**Fig. 5.** Impacts on the environment, animal welfare and human health of alternative diets to the reference diets of both men and women in North-Rhine Westphalia (RD), namely recommended diet by the German Nutrition Society (DD); vegan diet (VD) and Mediterranean diet (MD): (a) climate change, (b) fine particulate matter formation, (c) terrestrial acidification, (d) freshwater eutrophication; (e) marine eutrophication, (f) land occupation, (g) fossil resource scarcity, (h) water use; (i) Animal Life Years Suffered (ALYS), (j) loss of Animal Lives (AL); (k) loss of Morally-adjusted Animal Lives (MAL); (l) impacts on human health (DALYs).

The reduction in animal-based products consumption contributes greatly to lower environmental impact values for most indicators in RD, MD and VD. These results are aligned with many LCA studies evaluating the contribution of animal-based products to environmental impacts such as climate change (Batlle-Bayer et al., 2020; Bruno et al., 2019; Heller et al., 2018). According to Sandström et al. (2018), the share of animal-based products within a diet is a good measure of its environmental footprint. This study also shows that typical Western diets cause greater impacts than vegetarian options (Chapa et al., 2020; Goldstein et al., 2016). Within the EU context, reducing meat (especially beef) and dairy products could remarkably reduce several consumption-based environmental impacts and improve human nutrition (Beylot et al., 2019; Chaudhary et al., 2018; Sala and Castellani, 2019; Sandström et al., 2018). Moreover, this study reveals that an increased consumption of other animal-based products such as fish and honey can have negative animal welfare implications, based on the indicators from Scherer et al. (2018). In this sense, normalization and weighting among OH dimensions could help identify more sustainable diets, but this requires arbitrary choices and remains an open challenge in LCA (Hélias and Servien, 2021; Roesch et al., 2020).

Although LCA case studies assessing animal welfare are scarce, outcomes from this study are consistent with the framework of Scherer et al. (2019, 2018), which attributes higher impacts to small animals. This captures how, for instance, the treatment of fish and seafood in industrial aquaculture can be extremely unethical, with a scale of damage greater than the suffering in conventional land-based animal farms (Berlinghieri et al., 2021; Rodríguez, 2010). The concerns on the relation between fish welfare, profitable production and the increase of the mortality rate among farmed fish over the past years remain as an open ethical question (Størkersen et al., 2021). Acute and chronic stressors, high stocking densities and environmental conditions (i.e., water acidity) in aquaculture systems generate social, swimming, and foraging behaviour changes (i.e., aggressiveness and competition). This also poses negative neurological and physiological effects, by decreasing health conditions with injuries, diseases, parasitic infestations (i.e., fish lice); which overall translate into an increased mortality rate (Berlinghieri et al., 2021; Jensen et al., 2020; Størkersen et al., 2021; Toni et al., 2019). Although the neural structure for phenomenal consciousness of fish and shrimps withdraws the full experience of physical pain (Key, 2015), there is enough evidence on the development of learning mechanics to avoid unpleasant experiences, indicating sensation of pain (Braithwaite, 2010; Sneddon, 2015). Similarly, the lifespan of honeybees is dramatically reduced in intensive honey production systems, especially during the summer when honey production peaks (Litmann et al., 2016; Schroeder, 2014). It should be highlighted that potential ecological benefits of beekeeping, including the provision of ecosystem services like pollination, are not considered in this study but should be taken into account for further sustainability assessments (Gaines-Day and Gratton, 2016; Vrabcová and Hájek, 2020).

It is particularly noteworthy that the RD in NRW is more detrimental to human health than the proposed alternative dietary scenarios. Two main factors contribute to diabetes and cardiovascular diseases: the high intake of animal-based and energy-dense foods, combined with the low intake of plant-based foods. Several studies show the relation between red meat intake and a higher risk of metabolic syndrome, obesity and diet-related NCDs, including coronary heart disease, stroke, and diabetes mellitus (Azadbakht and Esmaillzadeh, 2009; Micha et al., 2010; Rouhani et al., 2014). The use of dietary risk factors is a good measure of human health impacts, in which vegetarian meals present a lower disease burden than meals containing meat (Weidema and Stylianou, 2020). As an additional finding, women's diet turned out to be more aligned with healthier standards than men's, corroborating results from earlier German studies (Meier and Christen, 2013; Treu et al., 2017). Another important aspect to consider is alcohol intake in Western diets. Although the GBD considers alcohol consumption as a behavioural risk factor (i.e., not as a dietary risk factor), alcoholic beverages are part of dietary patterns, especially among men and younger segments of the population (Nasreddine et al., 2021; Wilsnack et al., 2009). Alcohol consumption has been associated with stroke, some types of cancers and other disorders (GBD 2019, 2020).

Specific improved dietary scenarios could be developed or designed adequately for particular population groups and geographical locations (Hallström et al., 2015). Sustainable food consumption patterns and consistent dietary recommendations, proper site monitoring and communication along the supply chain are part of the solutions to effectively reduce impacts derived from food production and consumption (Poore and Nemecek, 2018). The dilemma between sustainability and economic performance arises when rethinking dietary implications of shifting from animal- to plant-based options (Marques et al., 2018). Strategies along the food chain, such as technological improvement towards mitigation of environmental impacts and food waste, should align with socio-economic development and consumer-oriented strategies (Notarnicola et al., 2017a; Springmann et al., 2018). The effectiveness of supply-side measures is limited if consumers keep choosing high-impact products (Poore and Nemecek, 2018). However, influencing consumers' choices entails a substantial challenge, which could be partially overcome by communicating simplified outcomes from complementary scientific analyses, to enhance education, dialog and public awareness (Helander et al., 2021; Karlsson Potter and Röös, 2021). A sustainable development path towards changing consumption patterns within the EU requires an overall decoupling of environmental impacts from economic growth, combining sustainability metrics and economic indicators that could easily be integrated into decision-making (Sanyé-Mengual et al., 2019).

### 4.2. Methodological limitations and societal implications

Integrating the OH approach into LCA of food diets poses additional methodological challenges and limitations. The first one relates to data availability and representativeness, since detailed and updated data on food consumption is not always available at sub-national scales, even within the EU context. The need to use the National Nutrition Survey (NVS II) (Max Rubner Institut, 2008) as the most recent and comprehensive data on food consumption at the German federal state level is a clear example. Carrying out bottom-up LCA of food consumption in NRW entailed making assumptions to fill data gaps, for instance, by using additional national-level data from Treu et al. (2017). Additional subjective choices applied to allocate specific products into major food categories come with the associated uncertainty. On the one hand, the RD might overlook important aspects of food insecurity by omitting unintentionally vulnerable groups from the surveys (Pfeiffer et al., 2015). On the other hand, Optimeal® relies on FAOSTAT data to estimate the average crop mix and the origin of products from 2009 to 2013. Yet, the resulting RDs can still be considered representative of the prevailing food consumption habits in NRW. Despite data gaps, taking a sub-national scope can help assess sustainability implications of diets, especially for large and heterogeneous countries like Germany, as food consumption is subject to geographical and socio-economic variabilities (Mertens et al., 2018). For instance, in Germany, recent data shows that the observed decrease in meat consumption differs across federal states and is driven by dietary shifts towards more plant-based options, motivated by sustainability concerns (BMEL, 2021; Davis and Geiger, 2017; Pfeiffer et al., 2015). When collecting survey data on diets, it is important to capture gender and age factors and underlying relationships between food consumption habits and sustainability outcomes. Therefore, it is recommended to gather regional life cycle inventories through primary data as far as possible to capture both spatial and temporal variability in food consumption (Heller et al., 2018). However, this comes with enormous data collection needs that justify the scarce literature on bottom-up LCA case studies of diets based on primary data.

The present study performs uncertainty analysis through Monte Carlo simulation to understand results variability due to variability in food consumption in alternative diets. Further results uncertainty is still to be expected from the use of average LCIs and impact-intensity coefficients per food item in Optimeal® (Broekema et al., 2019). These may not represent spatial and temporal variability in upstream impacts depending on the country of origin of the respective food products and underlying production and transportation systems. However, the methodology applied by Optimeal® avoids the need to carry out an LCA per each food product included in the respective diets, while being largely consistent with the PEF framework. It must be noted that impacts from land transformation or LUC-related emissions are not included, which are intrinsically linked to deforestation and soil degradation occurring mainly in developing countries that export agricultural commodities to international markets (Crippa et al., 2021). Deforestation is a significant driver of GHG emissions embodied in consumption-based footprints of high-income countries when considering international agri-food trade (Escobar et al., 2020; Sandström et al., 2018). Including LUC would require additional assumptions to retrospectively estimate the land types and areas converted in the sourcing regions of each product; with the associated uncertainty, especially in the case of large-scale analyses like the present one. The overall environmental impact derived from food consumption at the regional level might be even higher if the diets would also include consumption in other sectors (outside the household), such as gastronomy, tourism, education, social, and health care services (Beylot et al., 2019). It must also be noted that system boundaries do not include end-of-life (e.g., human excretions, wastewater treatment), which generate additional environmental burdens (Notarnicola et al., 2017b). Including food waste disposal is particularly key in addressing overall food systems' sustainability and the implications of EU food waste reduction strategies (Esposito et al., 2016; European Commission, 2017; Helander et al., 2021). Several studies propose new methods to estimate waste along the supply chain in the EU, underlining the importance of improving the evaluation of critical sectors from processing to the household, where plant-based foods are mostly wasted (i.e., cereals, fruits and vegetables) (Caldeira et al., 2021, 2019; De Laurentiis et al., 2020).

Human toxicity impacts were not assessed among the environmental impact categories due to limitations of the dataset, which does not consider pesticide production and use within the system boundaries. In any case, toxicity impacts are product-specific and largely influenced by climatic conditions, which hinders the consideration in large-scale LCAs of food systems. Human toxicity (cancer- and non-cancer-related) impacts from food consumption have been mainly linked to metal particle emissions from agriculture and food products (Beylot et al., 2019). Human toxicity estimation in LCIA could benefit from more sophisticated non-linear characterization methods to determine human health impacts caused by emissions and exposure to pollutants and chemicals throughout the life cycle (Li et al., 2020). Additionally, the DALY indicator considers human health implications without looking into potential health benefits from nutrition, in spite of the fact that nutrients and food items (or the lack of them) can be a risk factor to human health. For example, nutrient profiling and nutrient scores qualify and disqualify nutrients from meeting quantity, quality, and satiety (Weidema and Stylianou, 2020). Refined human health indicators could potentially be applied in LCA, such as “DALY-Nutrition-Index”, to assess DALYs per individual food item (or meal) as nutrition-health damage at the endpoint level (Weidema and Stylianou, 2020). Other examples include “Nutrient-Rich Foods Index 9.3”, “Nutritional Quality Index”, and “Fullness Factor” to assess several nutrition-based FUs in terms of nutrition quality and satiety (Chapa et al., 2020).

The lack of standardized metrics on the impacts on animals in LCA makes it difficult to measure animal welfare in quantitative terms (Notarnicola et al., 2017b). Including animal welfare indicators in LCA raises ethical considerations, where complexity and inconsistency of comparable data and scientific consensus make the analysis even more challenging (Tallentire et al., 2019). The whole issue on the criterion *number (of animals) affected* implies discussing the absolute number of lives lost versus the animals' utility to humans. As Gustaf et al. (2017) explain, either methods should be revised or improved, or more consensus is needed on ethical questions about the value of the lives of animals whose purpose is the production of food for humans. Indeed, a more scientific or ethical consensus is required to justify animals' moral treatment and agree on a better definition of an absolute animal welfare indicator (Phillips and Kluss, 2018; Tallentire et al., 2019).

## 5. Conclusions

This study proposes integrating the OH into an extended LCA to assess the sustainability of dietary patterns in NRW (Germany), with the ultimate goal of identifying more sustainable food consumption alternatives to typical Western diets. The RDs of both men and women in NRW are compared to three improved scenarios to represent a shift towards healthier dietary patterns by using quadratic optimization under nutritional constraints. The three scenarios deliver sustainability gains relative to the RD, although trade-offs arise. On the one hand, replacing animal-based with plant-based protein sources can increase water scarcity. On the other hand, an increased consumption of animal-based products such as fish, seafood and honey has negative implications for animal welfare, given the larger number of animals that suffer. This highlights the role that the choice of animal-based products plays in the overall sustainability of Western diets from a OH perspective. Regardless of the choice of animal-based protein sources, the larger the share of plant-based foods – such as fruits, vegetables, legumes and whole grains – in a diet, the greater the associated human health benefits. Moreover, reducing consumption of ready-to-eat meals and highly processed foods is clearly recommended to improve the health of humans, animals and the environment at the same time.

Implementing systemic approaches such as OH into LCA comes with many methodological challenges derived from the availability of reliable and comprehensive food consumption statistics, associated LCI data and LCIA methods. This study highlights the need to a) provide comprehensive LCI data in commercial databases that capture spatial variability in agri-food production systems globally; b) develop consensus-based LCIA methods for animal welfare and diet-related human health indicators; and c) make information on consumers' choices available for facilitating forward-looking assessments of supply- and demand-side impact mitigation measures at different geographical scales. As for the estimation of animal welfare, it is particularly important that commercial LCI databases include data on farm conditions, animal health and wellbeing; which are still scarce, scattered and often confidential. Additionally, ethical and societal aspects emerge, which may require the application of complementary methodologies, given the lack of scientific consensus and comparable quantitative indicators. In this sense, improving OH approaches to LCA could greatly benefit from interdisciplinary collaboration at the intersection between life and social sciences to tackle interlinked human and natural complexities. Considering other life cycle stages such as LUC and end-of-life is desirable to estimate impacts of Western diets from cradle-to-grave and inform decision-making in the EU towards the EU Green Deal and the Sustainable Development Goals. Yet, communication of outcomes to influence consumers' choices remains especially challenging in multi-dimensional sustainability assessments like the one proposed by this study from a OH perspective.

## CRediT authorship contribution statement

**Juliana Minetto Gellert Paris:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Validation. **Timo Falkenberg:** Conceptualization, Supervision, Funding acquisition, Writing – review & editing. **Ute Nöthlings:** Conceptualization, Supervision, Writing – review & editing. **Christine**

**Heinzel:** Conceptualization, Writing – review & editing. **Christian Borgemeister:** Conceptualization, Supervision, Funding acquisition, Writing – review & editing. **Neus Escobar:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Supervision, Validation.

## Declaration of competing interest

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

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## Appendix A. Electronic supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.151437.

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