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Greenhouse gas emissions of environmentally sustainable diets: Insights from the Icelandic National Dietary Survey 2019–2021

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ABSTRACT

Background: Health authorities are increasingly integrating environmental sustainability considerations into food-based dietary guidelines. However, concerns persist about the accuracy of the data used to assess environmental impacts, as well as the extent to which these guidelines are followed in practice.
Aim: To compare dietary greenhouse gas (GHG) emissions estimates using different top-down and bottom-up life cycle assessment (LCA) databases; and to estimate GHG emissions of food consumption within the ranges set for meat and dairy in recently proposed environmentally sustainable diets.
Methods: Dietary GHG emissions were estimated for participants in the 2019–2021 Icelandic National Dietary Survey (n = 822) using three publicly available LCA databases from Denmark, the US, and France. GHG emissions among participants whose consumption was aligned with the EAT-Lancet diet, the 2021 Danish food-based dietary guidelines and the 2023 Nordic Nutrition Recommendations were also quantified.
Results: The mean dietary GHG emissions among participants were 6.3, 6.1, and 6.1 kg CO_2-eq/day based on the Danish (top-down), US (bottom-up), and French (bottom-up) databases, respectively. The relative ranking of foods was also consistent across all three databases. For example, the relative contribution of total CO_2-eq (% range for the three databases) was highest for red meat (39–51%), followed by dairy (10–17%) and beverages (9–13%). The contribution from plant-based foods (6–10%), seafood (4–11%), and poultry/eggs (<5%) was modest. The dietary habits of most participants (86%) were outside the ranges for meat and dairy consumption as set by the three sustainable diets. However, participants reporting consumption within the ranges for meat and dairy had mean GHG emissions ranging between 4.2 and 4.7 kg CO_2-eq/day, depending on the diet. In comparison, the mean for participants not adhering to the sustainable diets was 7.7 kg CO_2-eq/day. These results are higher than those reported in other Nordic and European studies, likely due to high consumption of lamb, beef, and dairy, and low consumption of plant-based food.
Conclusion: All three LCA databases provided similar estimates for total dietary GHG emissions and relative ranking of different food groups. Based on current dietary habits in Iceland, adherence to environmentally sustainable diets would lead to a substantial reduction in dietary GHG emissions.

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1. Introduction

Public awareness of environmental impacts of foods has led to growing interest in more environmentally sustainable plant-based diets (Alcorta et al., 2021; The Economist, 2020). One commonly used measure of environmental impact is the carbon footprint, defined as the amount of carbon dioxide equivalents released per kilogram of a food product. Based on this measure, global food production is estimated to account for between 20 and 30% of total greenhouse gas (GHG) emissions (Crippa et al., 2021; Rosenzweig et al., 2020; Xu et al., 2021). In comparison, global aviation accounts for around 2% (Ritchie, 2020). Carbon footprints of foods are assessed using life cycle assessment (LCA), which estimates the total GHG emissions over the product's lifetime from farming, processing, packaging, transporting, storage to final disposal (Lamnatou et al., 2022). However, for a given food product assumptions on the underlying system boundaries and representative farming systems may lead to varying GHG emissions estimates (McLaren et al., 2021). This has led to some discussion on the reliability of LCA data for drawing robust conclusions on dietary GHG emissions (Carvalho et al., 2023; Poore and Nemecek, 2018; Sugimoto et al., 2021; Trolle et al., 2022).

With estimates of GHG emissions for different food products becoming widely available (Cai et al., 2022), environmental considerations are increasingly being integrated by researchers and public health authorities when developing food-based dietary guidelines (FBDGs). Recent examples include the EAT-Lancet planetary health diet (Willett et al., 2019), the 2021 Danish FBDGs (Danish Veterinary and Food Administration, 2021) and the 2023 Nordic Nutrition Recommendations (NNR) (Blomhoff et al., 2023). Whether people adhere to such recommendations is difficult to predict. Yet one way of estimating the environmental impacts of diets in real-life settings is to quantify their GHG emissions measured in representative national dietary surveys (Rose et al., 2019).

As reported in several different studies, the carbon footprint associated with dietary habits in the Nordic countries is relatively large compared with other European countries (Gonzalez-Garcia et al., 2018) due to high consumption of red meat and dairy (Irz et al., 2024; Lengle et al., 2024; Trolle et al., 2022). Iceland is largely self-sufficient in meat and dairy production, although these food systems are vulnerable due to dependency on feed and fertilizer imports (Sturludóttir et al., 2021). The country is also self-sufficient in seafood but relies heavily on imports for most other foods. Existing data suggests that the meat, dairy and seafood production systems are not much different from the Nordic countries with similar GHG emissions (Meltzer et al., 2024). However, unlike the other Nordic countries, the GHG emissions associated with dietary habits in Iceland have not previously been quantified.

This study had three specifics but overlapping objectives. Firstly, to quantify the GHG emissions associated with current dietary habits in Iceland. For that purpose, we used the Icelandic National Dietary Survey (2019–2021). Based on this survey, as our second objective, we assessed dietary GHG emissions among participants whose diets fell within or outside the ranges set for meat and dairy by recently proposed guidelines on diet and environmental sustainability (Blomhoff et al., 2023; Danish Veterinary and Food Administration, 2021; Willett et al., 2019). Thirdly, we assessed if the same conclusions on dietary GHG emissions could be obtained by using three publicly available LCA databases that differ by their design and underlying assumptions.

2. Material and methods

2.1. The Icelandic national dietary survey (2019–2021)

Participants were recruited based on a random sample from the National Registers Iceland (þjóðskrá), which keeps a record of all ~375.000 inhabitants. Eligible participants were all subjects aged 18–80 years, living in Iceland during the recruitment period (September 2019 to February 2021), who could communicate in either Icelandic or English. Of the 1545 eligible participants contacted, 822 agreed to participate (53%).

The dietary assessment consisted of two 24-h dietary recalls and a short food frequency questionnaire along with questions on sociodemographics, lifestyle, and health (Gunnarsdóttir et al., 2022). The two 24-h dietary recalls were conducted as phone interviews by trained researchers and were sampled on two non-consecutive days to capture variations in intake between weekends and weekdays.

2.2. LCA data on GHG emissions

Three open-source LCA databases from Denmark, the US, and France were used to assess the GHG emissions of our study participants' diets:

The Danish *CONCITO* database: This top-down database was launched in 2021 (The Big Climate Database, 2021). The GHG emissions of individual food were assessed through hybrid consequential LCA input-output analyses. The database contains estimates of the GHG emissions of ~500 individual food items found in Danish grocery stores. The selection of products also covers imported food items widely sold on the European market, including Iceland. The database quantifies the total GHG emissions (in kg CO_2-eq) associated with producing one extra kg of a given food item, which is then subdivided into contributions from agriculture, indirect land-use change (ILUC), processing, packaging, transport, and retail trade. This allowed for evaluation of GHG emissions at each stage in the food supply chain independently. Food loss occurring across the food supply chain is not included in this database. The functional unit is per kg product bought by the consumer. A more detailed description can be found in the methodology report (Schmidt et al., 2021).

The US *dataFIELD* database: This bottom-up database was launched in 2017 (dataFIELD, 2018). It was in part constructed to assess GHG emissions of diets as reported in the US National Health and Examination Survey (Rose et al., 2019). The database consists of data extracted from different LCA studies published between 2006 and 2015 covering ~330 different food commodities. The authors state that the GHG emissions values assigned to each food commodity should reflect generic average environmental impacts associated with the production of those foods as sold in the United States, even though some values are based on studies conducted outside the US. Contribution from packaging, distribution, retail, and food loss were not included in this database (only emissions associated with production). The functional unit is per kg of food, which in the case of fish and meat refers to edible (boneless) weight. A more detailed description of the database can be found elsewhere (Heller et al., 2018).

The French *AGRIBALYSE* database: This bottom-up database was initially launched in 2013 and provides information on the environmental impacts of over 2500 food items that are included in the French food composition table *CIQUAL* and consumed in France (AGRIBALYSE, 2020). The functional unit is kg of prepared food products as consumed. The GHG emissions estimates accounted for most stages in the value chain from raw material production to food preparation at consumer level (i.e., energy used for cooking). Food loss and waste at various stages across the food supply chain up to and including retail level were also accounted for in this database. A more detailed description of the methodology can be found elsewhere (Asselin-Balençon et al., 2022; Colomb et al., 2015).

2.3. Dietary GHG emissions calculation

The dietary assessment consisted of two 24-h dietary recalls, where the mean of the two recalls was used as a measure of habitual dietary intake. The amounts of foods and nutrients consumed were then calculated by linking the consumption of individual or composite food items (as recipes) with the Icelandic food composition table (ÍSGEM, 2011). The associated GHG emissions were then estimated by

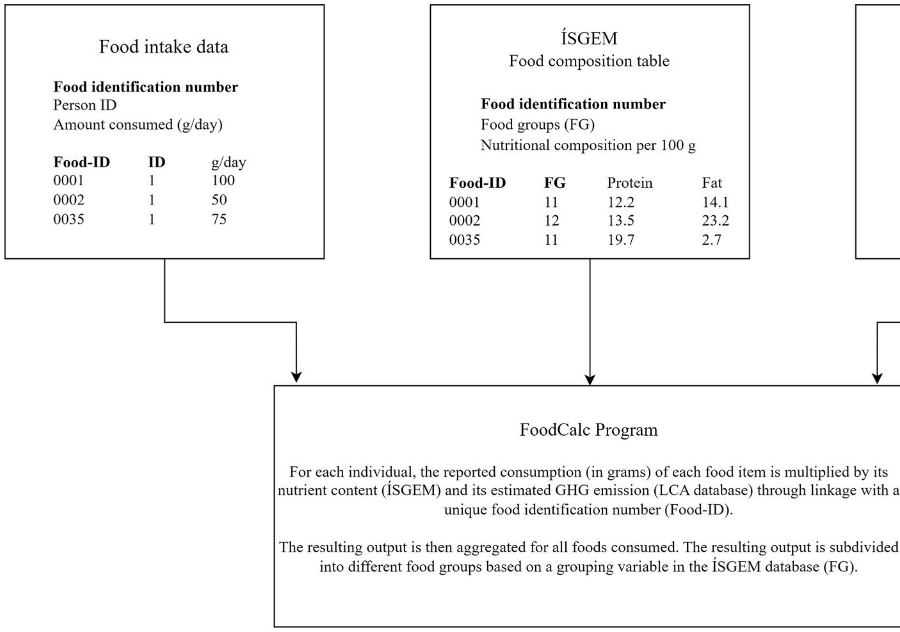

Fig. 1. Description of the dietary calculation showing how data on food intake were linked with the food composition table (ÍSGEM) and the LCA databases containing information on GHG emissions.

Table 1
Cut-off criteria used to assess the adherence to the three dietary guidelines where sustainability has been integrated. Used in calculating the participant's dietary GHG emissions.

	Eat-Lancet	Danish FBDGs	NNR 2023
Dairy	≤500 g/day	≤250 g/day	≥350 and ≤ 500 g/day
Red meat	≤196 g/week		≤350 g/week
White meat	≤406 g/week		
All meat		≤350 g/week	

The complete boundaries for these diets are reported in Table A.1.

introducing an additional variable, one for each database, into the food composition table with numeric values for the GHG emissions associated with the production of each food item (in kg CO_2-eq per 100 g food). Calculations were performed using the *FoodCalc v1.3* software (Fig. 1), developed for large-scale dietary surveys by the Danish Cancer Society (Lauritsen, 1998). Allocation of foods into different food groups was based on the grouping used in the 2019–2021 Icelandic National Dietary Survey (Gunnarsdóttir et al., 2022) with slight modification, to allow for more detailed separation of different meat products.

For the values reported in the French *AGRIBALYSE* database, weight loss or gain during food preparation, food waste and losses up to and including retail level had already been considered (AGRIBALYSE, 2020). To make the results for the three databases more comparable, food waste and losses up to and including retail level were added to the Danish *CONCITO* and US *dataFIELD* databases. This was done by using standard values based on a report published by the U.N. Food and Agriculture Organization (FAO, 2011). In our dietary calculations weight loss or gain during food preparation were also accounted for (i.e. loss or gain of water and fat). This is a standard approach in such dietary calculations and is either already included in the food composition databases, as was the case for the French database, or added during the dietary calculations. In summary, all dietary intake estimates reported in this study, including the dietary GHG emissions, refer to the edible part of the food as consumed after food preparation. All dietary GHG emissions estimates for the Danish *CONCITO* and US *dataFIELD* databases have also been adjusted for food loss and waste up to retail level making the system boundaries more comparable to that of the French *AGRIBALYSE* database. The corresponding estimates without adjustment for waste and food loss up to retail level for the Danish *CONCITO* and US *dataFIELD* databases (their original system boundaries) are also provided in supplemental material.

2.4. Environmentally sustainable diets

Participants were grouped according to whether their dietary consumption fell within the ranges set for meat and dairy (Table 1) as outlined in the three recently published dietary guidelines: 1) The EAT-Lancet planetary health diet (Willett et al., 2019), 2) the 2021 Danish FBDGs (Danish Veterinary and Food Administration, 2021) and 3) the 2023 Nordic Nutrition Recommendations (Blomhoff et al., 2023). All three dietary guidelines aim at ensuring optimal nutritional status while considering environmental sustainability to varying extents. The reason for only considering ranges for meat and dairy was because these two food groups usually have the highest relative environmental impact (Blomhoff et al., 2023; Danish Veterinary and Food Administration, 2021; Willett et al., 2019), and applying the full boundaries of these diets (Table A.1) would result in much higher exclusion rate.

2.5. Statistics

Data were described using numbers and percentages for dichotomous variables and as means and standard deviations (SD) for continuous variables. Distribution of variables was assessed by visual inspection of histogram, Q-Q plots, and confirmed by the Shapiro-Wilk test ($p < 0.05$ for all variables). The *t*-test and the Kruskal-Wallis *H* test were used in examining differences between groups for normal and skewed outcome distributions, respectively. Upon significant results with the Kruskal-Wallis test ($p < 0.05$), post hoc analysis was conducted to identify which databases differed from each other using a Dunn's test with a Bonferroni correction to control for multiple comparisons. The Fisher's exact test was used in examining the significant difference for categorical variables across the diet groups. All calculations were performed in R and executed in R-Studio Posit software (version 2023.08.0).

The participants' dietary intake was estimated as the amount of food consumed in grams per day, and total food intake was divided into

Table 2
Demographic information based on the Icelandic National Dietary Survey 2019–2021.

	All	Male	Female
n (%)	822 (100%)	394 (48%)	428 (52%)
Age (years), n (%)			
18-39	240 (29%)	118 (30%)	122 (29%)
40-59	319 (39%)	143 (36%)	176 (41%)
60-80	263 (32%)	133 (34%)	130 (30%)
Mean (SD)	50 (16)	50 (16)	50 (16)
Education, n (%)			
Primary School	139 (17%)	62 (16%)	77 (18%)
Upper secondary school	254 (31%)	150 (38%)	104 (24%)
University degree	362 (44%)	145 (37%)	217 (51%)
Other	67 (8%)	37 (9%)	30 (7%)
Smoking, n (%)			
Yes	73 (9%)	36 (9%)	37 (9%)
No	749 (91%)	358 (91%)	391 (91%)
BMI (kg/m^2), n (%)			
<18.5	6 (1%)	3 (1%)	3 (1%)
18.6–24.99	277 (34%)	107 (27%)	170 (41%)
25–29.99	332 (41%)	184 (47%)	148 (36%)
>30	190 (24%)	96 (25%)	94 (22%)
Mean (SD)	27.1 (4.7)	27.7 (4.4)	26.3 (5.0)
Residence, n (%)			
Reykjavik capital area	523 (64%)	242 (61%)	281 (66%)
Rural area	299 (36%)	152 (39%)	147 (34%)

Abbreviations: BMI - Body Mass Index.

different food groups, reflecting intake of different animal-based foods, plant-based foods, and confectionery products. Similarly, for all three databases, dietary GHG emissions (in kg CO_2-eq/day) were estimated for both total food consumption and as contribution from individual food groups. In addition, the relative contribution of agriculture, ILUC, processing, packaging, transport, and retail to total dietary GHG emissions was estimated using the Danish *CONCITO* database (this information was not included in the other two databases).

To account for possible underreporting of dietary intake, we estimated the energy requirement of each participant using the Harris-Benedict equation (Roza and Shizgal, 1984), calculating the basal metabolic rate based on their sex, age, height, and weight. Physical activity levels (PAL) were assumed to be low to moderate for all participants (PAL of 1.4) (Westerterp, 2013). When, comparing the GHG emissions associated with different diets, results were presented as unadjusted and adjusted for sex and estimated energy requirement.

3. Results

3.1. The Icelandic national dietary survey

The demographic characteristics of the study participants are shown in Table 2. The mean age was 50 years (range: 18–80 years) and 52% of participants were females. The prevalence of overweight and obesity was 41% and 24%, respectively. A total of 44% of participants reported to have a higher education, which is nearly identical to the national average of 43% (OECD, 2023). Around 64% of participants lived in the greater Reykjavik capital area, which is largely in accordance with the statistics on the population from 2023 (Statistics Iceland, 2023). The mean total dietary GHG emissions for participants across the demographic characteristics are shown in Table A.2.

3.2. Dietary GHG emissions

The mean (SD) total dietary GHG emissions based on the Danish *CONCITO* (DK), *dataFIELD* (US) and French *AGRIBALYSE* (FR) databases were 6.3 (4.8) and 6.1 (3.6) and 6.1 (2.9) kg CO_2-eq/day, respectively (Fig. 2). No significant difference was observed when comparing the DK and US ($p = 0.66$) and US and FR ($p = 0.11$) databases, while mean values for the DK and FR databases were significantly different ($p = 0.03$). The unadjusted values for the DK and US databases were ~10% lower based on their original system boundaries where contribution of food loss and waste up to retail level was not included (see suppl. Table A.3). Based on the DK database (Fig. B.1), contribution of agriculture and associated ILUC accounted for ~70% of total mean dietary GHG emissions while other factor such as transport and packaging contributed much less (<10% each) When comparing the GHG emissions for different food groups (Table 3), the highest contributions were

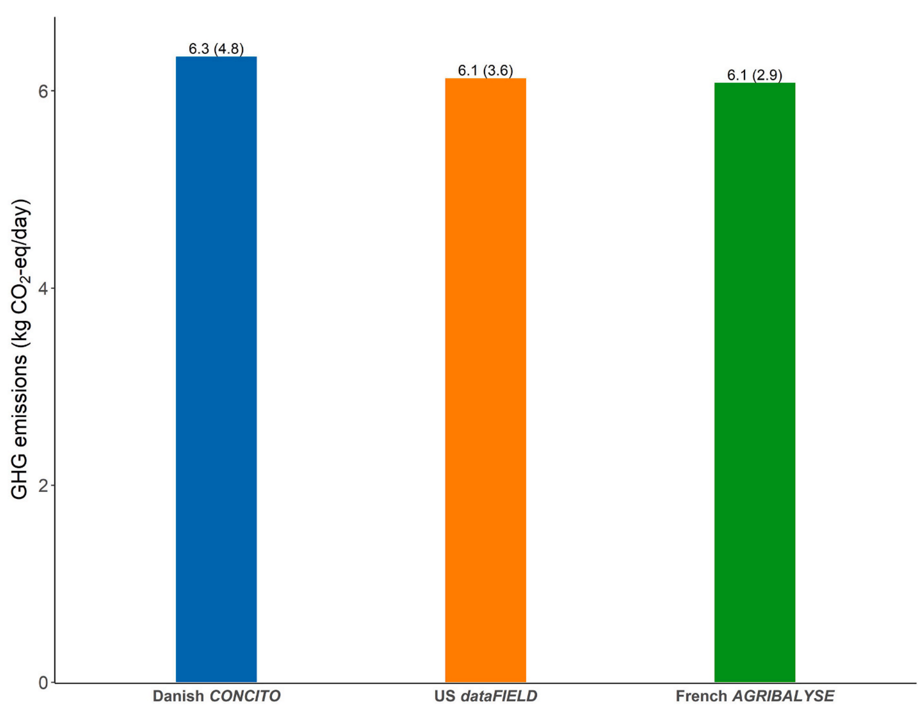

Fig. 2. Total dietary GHG emissions, in kg CO_2-eq/day, for survey participants as assessed using the three different LCA databases: the Danish *CONCITO*, US *dataFIELD* and the French *AGRIBALYSE* databases. The mean (standard deviation) is reported above each bar.

Table 3
Dietary GHG emissions (kg CO_2-eq/day) among participants in the Icelandic National Dietary Survey 2019–2021. Mean (SD) GHG emissions for food groups after adjusting for food loss[a], data are shown for the three databases.

Food groups	Consumption	Danish *CONCITO*	US *dataFIELD*	French *AGRIBALYSE*
	Mean (SD) g/day	Mean (SD)[b] kg CO2-eq/day		
Beef and veal	25 (41)	1.79 (4.30)	1.03 (1.79)	0.97 (1.66)
Lamb and mutton	24 (47)	1.00 (1.96)	1.26 (2.48)	1.03 (1.99)
Pork and pig	24 (36)	0.23 (0.36)	0.27 (0.40)	0.27 (0.43)
Other red and processed meat	7 (25)	0.21 (0.88)	0.26 (0.94)	0.09 (0.42)
Poultry and eggs	55 (62)	0.17 (0.22)	0.29 (0.34)	0.25 (0.31)
Seafood	44 (57)	0.73 (0.97)	0.24 (0.49)	0.54 (0.88)
Dairy products	312 (256)	0.64 (0.39)	1.02 (0.64)	0.90 (0.62)
Fruits	91 (104)	0.14 (0.16)	0.06 (0.07)	0.11 (0.13)
Cereals	168 (104)	0.23 (0.16)	0.18 (0.13)	0.30 (0.23)
Other plant-based sources[c]	184 (122)	0.26 (0.20)	0.15 (0.12)	0.22 (0.17)
Beverages	1630 (734)	0.55 (0.46)	0.79 (1.10)	0.82 (0.57)
All other foods	150 (113)	0.40 (0.27)	0.56 (0.65)	0.57 (0.55)

Abbreviations: CO_2-eq. - carbon dioxide equivalent. GHG emissions - greenhouse gas emissions.
The Danish *CONCITO* database launched in 2021 (The Big Climate Database, 2021).
US *dataFIELD* (database of Food Impacts on the Environment for Linking to Diets) launched in 2017 (dataFIELD, 2018).
The French *AGRIBALYSE* database launched in 2013 (AGRIBALYSE, 2020).
[a] Food loss was added to the Danish *CONCITO* and the US *dataFIELD* databases according to values reported by FAO.
[b] Using Kruskal-Wallis *H* test, comparison revealed no significant differences between the three databases for the food groups, Beef and veal, Lamb and mutton, Pork and pig, and Other red and processed meat. For all other food groups, the three databases were significantly different ($p < 0.05$).
[c] The food group "Other plant-based sources" excludes fruits and cereals.

consistently observed for foods of animal origin. For example, the mean GHG emissions associated with the mean consumption of 25 g/day for beef and veal were 1.79, 1.03, and 0.97 kg CO_2-eq/day for the DK, US, and FR databases, respectively. The mean GHG emissions for lamb and mutton (mean 24 g/day) was 1.00, 1.26, and 1.03 kg CO_2-eq/day for the DK, US, and FR databases respectively. The contribution of GHG emissions from dairy (mean intake of 312 g/day) was, however, estimated to be lower (0.64 kg CO_2-eq/day) in the DK database compared to the two other databases (1.02 and 0.90 kg CO_2-eq/day). The contribution of GHG emissions from poultry/eggs, pork meat, and seafood were much lower compared to the contribution from ruminant meat, and plant-based foods had by far the lowest footprint varying from 0.06 to 0.30 kg CO_2-eq/day depending on the database. Although mean values for individual food groups were in most cases similar across the three databases, significant differences in mean values were observed in all cases, except for the food groups: Beef and veal, Lamb and mutton, Pork and pig, and Other processed meat products.

Based on the Danish *CONCITO* database, the mean unadjusted dietary GHG emissions among participants reporting consumption within the ranges recommended for meat and dairy in the EAT-Lancet planetary health diet (n = 79), the 2021 Danish FBDGs (n = 29), and the 2023 NNR (n = 74) were 2.9, 3.0, and 3.3 kg CO_2-eq/day, respectively (Fig. 3). In comparison those (n = 706) with consumption outside of these ranges, or the prevalent diet, had mean dietary GHG emissions of 6.9 kg CO_2-eq/day. After adjusting for sex and participants' estimated energy requirement, the dietary GHG emissions ranged between 4.2 and 4.7 kg CO_2-eq/day for the three environmentally sustainable diets compared to 7.7 kg CO_2-eq/day for the prevalent diet. The corresponding estimates for the US and FR databases are shown in supplemental material (Figs. B.2 and B.3).

The dietary habits of participants within or outside the boundaries for red meat and dairy for the three environmentally sustainable diets are shown in Table 4. As per the definition of these diets, consumption of red meat was lower, while less pronounced differences were observed for dairy. Consumption of seafood among those adhering to these environmentally sustainable diets was similar with no significant difference compared to the prevalent diet. Subjects following the EAT-Lancet or the Danish FBDGs were less likely to be obese, although none were categorized as underweight (BMI<18.5 kg/m^2). Energy intake among subjects within the boundaries for red meat and dairy for the three environmentally sustainable diets was ~25–27% lower compared to the prevalent diet. However, no clear differences in the prevalence of those trying to lose weight were observed across the different diets (Table 4).

4. Discussion

Using three different publicly available LCA databases, nearly identical results were obtained for mean dietary GHG emissions among participants in the 2019–2021 Icelandic National Dietary Survey. Our results also showed that the intake of red meat and dairy contributed to more than half of the total dietary GHG emissions. Participants whose diets were within the ranges set for meat and dairy in the three recent dietary recommendations (Blomhoff et al., 2023; Danish Veterinary and Food Administration, 2021; Willett et al., 2019), which were partly constructed based on environmental sustainability considerations, had around half the GHG emissions compared to those outside those ranges.

After adjustments for food loss and waste up to retail level (Fig. 2.) all three databases provided similar estimates for total dietary GHG emissions, or within ~4% of each other. Slightly larger (~10%) differences were obtained without such adjustments (Table A.3). Despite adjustment, the three databases were still not fully aligned. For example, the French database included energy for cooking, which may account for up to ~3% of total dietary GHG emissions (Wolfson et al., 2022). Furthermore, the Danish database included contribution from ILUC (Chrintz and Minter, 2021), which was not included to the same degree in the other two databases. Due to differences in reporting, adjusting for these differences was not possible. Overall, a relative difference of ~10% between the three databases, based on their original system boundaries (Table A.3), should be a fair estimate of the between-database variability.

The modest difference between the three bottom-up (US and French) and top-down (Danish) databases in our study suggests that the choice of LCA methodology may be less important than other methodological issues such as selecting representative LCA studies. Still, there has been some discussion on the reliability of using top-down versus bottom-up LCA databases. The top-down approach uses economic models relying on industry data on consumption and value-added during production, which is then linked with environmental data on resource use. The resulting estimate is the impact of producing one extra unit of a given product. In contrast, the bottom-up approach assesses the impact of each step of the production process, with the resulting estimate being the

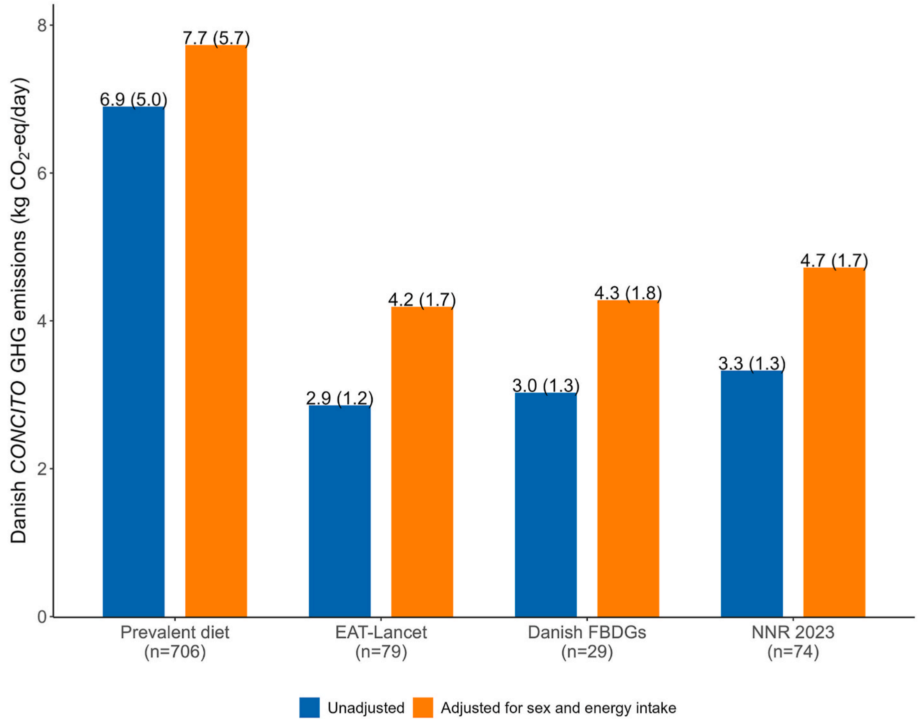

Fig. 3. Total dietary GHG emissions, in kg CO_2-eq/day, for survey participants whose consumption was within or outside the ranges set for meat and dairy products in the prevalent diet (outside ranges), EAT-Lancet (Willett et al., 2019), Danish FBDGs (Danish Veterinary and Food Administration, 2021); NNR 2023 dietary recommendations (Blomhoff et al., 2023). These estimates are based on the Danish *CONCITO* database. The mean (standard deviation) is reported above each bar and the results are shown as unadjusted and adjusted for sex and estimated energy requirement for each participant.

environmental impact of that production. Both methodologies have limitations; the bottom-up approach often lacks consistency in how different impacts are allocated across studies, while the top-down approach demonstrates greater sensitivity to the quality of market data employed for impact derivation (Sala et al., 2019; Schmidt et al., 2021). Apart from our study, two other studies (Sugimoto et al., 2021; Trolle et al., 2022) have compared dietary GHG emissions of certain diet (s) using production-based top-down versus bottom-up LCA databases. In both cases, the observed differences in total dietary GHG emissions were around 10%. Larger differences (~20%) have been observed in studies from the UK (Berners-Lee et al., 2012; Hoolohan et al., 2013) and the Netherlands (Temme et al., 2015; van de Kamp et al., 2018) when different bottom-up databases are applied to the same dietary data.

In our study, there are examples of notably different impacts observed between databases across food groups. Often such differences are related to study-driven assumptions on which food production system represents the consumer market. For example, in a study from Denmark (Trolle et al., 2022) the contribution to total dietary GHG emissions from meat and dairy was estimated at 57% and 10%, respectively, when the authors used the same top-down Danish *CONCITO* database as in our study. The corresponding numbers were 34% and 19% when the authors used their in-house bottom-up database. This lower impact for dairy estimated by the *CONCITO* database (also observed in our study), is partly related to the GHG emissions assigned to beef and dairy from dairy-producing cows. In the *CONCITO* database, this was done using the relative market price (Schmidt et al., 2021), while in the case of the bottom-up databases, biological factors are usually applied (Trolle et al., 2022). If everything else is equal, combined GHG emissions from beef and dairy should be the same regardless of how the relative impact was assigned. In the above-mentioned Danish study (Trolle et al., 2022), higher relative differences were observed for the in-house versus *CONCITO* database for beef and dairy combined (67% versus 53%), suggesting that different assumptions on the underlying production system were made. In their in-house database, Trolle et al. appear to have assumed that all beef came from domestic production, which is 90% dairy based (Mogensen et al., 2016, 2020). This resulted in a relatively low impact of ~13 kg CO_2-eq/kg being assigned to beef. However, it has been estimated that 40% of all beef products consumed in Denmark are imported (Mogensen et al., 2020) and such imports was accounted for in the *CONCITO* database. If only part of the beef import come from non-dairy cows (or cattle), that have at least twofold higher GHG emissions (Mogensen et al., 2016, 2020), this would explain the higher estimates derived from the *CONCITO* database. Similarly, the selection of LCA studies, chosen as representative of a given food production system, may well explain diverging estimates when comparing different databases using the same underlying dietary data, as reported in a recent study (Carvalho et al., 2023).

Participants' mean dietary GHG emissions of 6.1–6.3 kg CO_2-eq/day (depending on the database) are somewhat higher than what has been reported in other studies from the Nordic (Trolle et al., 2022) and European countries (Gonzalez-Garcia et al., 2018; Mertens et al., 2019). High consumption of lamb, beef, and dairy and relatively low consumption of plant-based foods in our study may account for part of these differences. Like our study, previous studies using national dietary surveys have consistently identified red meat and dairy as the two main contributors to dietary GHG emissions (Auclair and Burgos, 2021; Heller et al., 2018; Rose et al., 2019; van de Kamp et al., 2018; Vieux et al., 2012). For example, like our study, a Canadian study (Auclair and Burgos, 2021) reported that red meat contributed to 56% and dairy products to 14% of the total GHG emissions. Similarly, a US study (Heller et al., 2018) concluded that all meat products accounted for ~59% of the total GHG emissions and dairy accounted for ~18%. In these studies, the contribution from plant-based foods was marginal (<25%). However, as absolute intake values are not always reported comparably, a direct comparison across studies is difficult.

In line with these observations, GHG emissions were about 3.6–4.0 kg CO_2-eq/day lower among participants in our National Dietary Survey whose dietary habits were within the ranges set for meat and dairy in the

Table 4
Characteristics and dietary habits of participants in the Icelandic National Dietary Survey (2019–2021) who reported consumption within, or outside ranges proposed for meat and dairy in EAT-Lancet, Danish FBDGs, and NNR 2023 dietary recommendations.

	EAT-Lancet (n = 79)	Danish FBDGs (n = 29)	NNR 2023 (n = 74)	Prevalent diet[a] (n = 706)
Main characteristics				
Males, n (%)	18 (23%)	6 (21%)	19 (26%)	367 (52%)
Height, mean (SD)	169 (9)	169 (8)	170 (9)	174 (9)
Weight, mean (SD)	75 (14)	71 (13)	78 (15)	83 (18)
BMI (kg/m^2), n (%)				
<18.5	0 (0%)	0 (0%)	0 (0%)	6 (1%)
18.5–24.9	32 (42%)	15 (54%)	26 (36%)	231 (33%)
25–29.9	36 (47%)	12 (43%)	28 (39%)	285 (40%)
≥30	8 (11%)	1 (4%)	11 (25%)	170 (25%)
Trying to lose weight, n (%)	19 (24%)[f]	4 (14%)[f]	24 (32%)[f]	175 (25%)
Tried to lose weight within 12 months, n (%)	14 (18%)[f]	4 (14%)[f]	14 (19%)[f]	141 (20%)
Estimated energy requirement[b], kJ	8848 (1413)	8570 (1365)	9103 (1610)	9823 (1780)
Energy and macronutrients				
Energy intake, kJ	6431 (2310)	6641 (2736)	6850 (1941)	8869 (2930)
Protein, %E	15 (4)	14 (5)	17 (5)	18 (4)
Fat, %E	39 (9)	39 (10)[f]	40 (9)[f]	41 (8)
Saturated fat, %E	14 (4)	13 (4)	15 (4)	17 (4)
Carbohydrate, %E	42 (11)	42 (11)	40 (10)	36 (8)
thereof, fibers in g	16 (9)[f]	19 (12)	15 (7)[f]	16 (7)
Dietary intake, g/day		Mean (standard deviation)		
Red meat	6 (8)	7 (14)	18 (17)	91 (74)
Poultry	9 (18)	5 (14)	39 (57)[f]	36 (53)
Dairy products	298 (151)	122 (81)	426 (44)	711 (429)
Seafood	49 (60)[f]	58 (65)[f]	51 (55)[f]	43 (57)
Cereals	142 (104)[f]	149 (121)[f]	141 (90)	163 (104)
thereof, whole grains	66 (67)[f]	66 (61)[f]	71 (73)[f]	78 (85)
Fruits	117 (125)	165 (167)	86 (83)[f]	85 (101)
Vegetables	140 (129)[f]	177 (167)[f]	141 (96)[f]	166 (103)
GHG emissions,[c] kg CO_2-eq/day				
Red meat[d]	0.13 (0.28)	0.19 (0.52)	0.45 (0.62)	3.70 (4.92)
Poultry	0.04 (0.08)	0.02 (0.06)	0.16 (0.24)[f]	0.15 (0.22)
Dairy products	0.30 (0.15)	0.15 (0.11)	0.41 (0.08)	0.65 (0.38)
Seafood	0.80 (0.99)[f]	0.91 (1.03)[f]	0.83 (0.94)[f]	0.72 (0.97)
Cereals	0.20 (0.16)[f]	0.21 (0.19)[f]	0.20 (0.14)[f]	0.22 (0.15)
thereof, whole grains	0.09 (0.08)[f]	0.08 (0.07)[f]	0.10 (0.09)[f]	0.10 (0.11)
Fruits	0.18 (0.19)	0.23 (0.23)	0.13 (0.14)[f]	0.13 (0.15)
Vegetables[e]	0.19 (0.19)[f]	0.24 (0.21)[f]	0.21 (0.26)[f]	0.23 (0.16)

Abbreviations: BMI - Body Mass Index; CO_2-eq - carbon dioxide equivalent; GHG – greenhouse gas emissions; FBDGs - food-based dietary guidelines; NNR - Nordic Nutrition Recommendations; %E – % of total energy intake.
[a] The prevalent diets were those subjects outside the boundaries of red meat and dairy defined in the EAT-Lancet, Danish FBDGs, and the 2023 NNR.
[b] Estimated energy requirements calculated using the Harris-Benedict equation for basal metabolic rate and multiplied with estimated physical activity levels (PAL 1.4).
[c] Estimated using the Danish *CONCITO* database.
[d] The food group "Red meat" includes beef, lamb, and pork.
[e] The food groups "Vegetables" also includes tomatoes and potatoes.
[f] Variables not significantly different compared to the prevalent diet when using the *t*-test or Fisher's exact test (for categorical variables). All other variables are significantly different (p = 0.05).

three recently proposed environmentally sustainable diets (Blomhoff et al., 2023; Danish Veterinary and Food Administration, 2021; Willett et al., 2019) compared with those who consumed outside those limits. Participants following the EAT-Lancet ranges on meat and dairy had on average the lowest GHG emissions, and those following the 2023 NNR ranges had a higher impact. This difference is related to the restriction placed on red meat and dairy in these diets. The lower GHG emissions observed for the environmentally sustainable diets were, before adjustment, partly confounded by women being overrepresented, which to some extent explains the lower energy intake among participants following these diets. Studies have indicated that women might be more likely to make dietary changes with environmental considerations in mind (García-González et al., 2020), which may partly explain the gender imbalance in the three environmentally sustainable diets in our study. However, the differences in GHG emissions remained similar after adjusting for sex and participant energy requirements.

Finally, it is worth noting that the diets of participants within ranges set for meat and dairy in the three environmentally sustainable diets were neither vegetarian or vegan, as the daily consumption of dairy and seafood was quite high and the consumption of meat, although low, was above zero. Our results are also in line with a recent study from the UK based on ~55.000 participants from the EPIC-Oxford cohort, where vegetarians and low (<50 g/day) meat eaters had around 2.5- and 2-times lower carbon footprint compared to high (>100 g/day) meat eaters, respectively (Scarborough et al., 2023). In that study, higher environmental impacts like higher eutrophication potential, biodiversity, and land- and water use were also strongly associated with increased meat consumption. Several other studies have modeled the impact of replacing meat with plant-based foods (Mertens et al., 2021; Trolle et al., 2022; Vieux et al., 2012; Werner et al., 2014) or assessed the environmental impact of predefined fixed diets (Gonzalez-Garcia et al., 2018; Kovacs et al., 2021). Although benefits in terms of reduced carbon footprint with lower meat and dairy consumption have in all cases been observed, estimates from these studies have been quite diverse in terms of effect size and are often difficult to interpret. One limitation of these studies is that they are either based on several modeling assumptions, fixed predefined consumption patterns, or both. Such approaches may not capture how free-living people behave when it comes to dietary choices. The strength of our study is that we assessed the GHG emissions of three recently proposed environmentally sustainable diets in real-life settings and compared their impact with current mainstream dietary habits in our population. One limitation of our study is that few study participants were within the ranges for meat and dairy set by those diets. A larger study might better capture the variation that may exist within those diets.

5. Conclusion

In summary, our study shows that red meat and dairy have by far the highest dietary GHG emissions of any food group in the diets study population, while the contribution of dietary GHG emissions from plant-based foods was marginal. Our study also shows that adherence to the ranges set for meat and dairy in three recently proposed environmentally sustainable diets (Blomhoff et al., 2023; Danish Veterinary and Food Administration, 2021; Willett et al., 2019) has the potential to substantially reduce the dietary GHG emissions compared to the prevalent dietary habits. Based on the result from our study, adherence to these dietary guidelines would correspond to somewhere between 1.1 and 1.3 tons CO_2-eq reduction per person per year. This is important as these diets are designed to ensure optimal nutritional status and allow for considerable flexibility in dietary choices. In comparison, it has been estimated that the average emissions from all sources for an individual in the European Union is around 5.5 tons of CO_2-eq per year (The World Bank, 2020). Our study also highlights the need for monitoring real-life adherence to such diets as opposed to relying on varying modeling assumptions to predict the changes and identify and analyze real-life drivers and barriers to adopting and continuing such diets.

CRediT authorship contribution statement

Ragnhildur Guðmannsdóttir: Writing – original draft, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Steina Gunnarsdóttir:** Writing – review & editing, Investigation. **Ólöf Guðný Geirsdóttir:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **María Gudjónsdóttir:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Ingibjörg Gunnarsdóttir:** Writing – review & editing, Methodology, Investigation. **Hólmfríður Þorgeirsdóttir:** Writing – review & editing, Methodology, Investigation. **Jóhanna Eyrún Torfadóttir:** Writing – review & editing, Methodology, Investigation. **Michael Søgaard Jørgensen:** Writing – review & editing, Methodology. **Monia Niero:** Writing – review & editing, Methodology. **Amanda Wood:** Writing – review & editing, Methodology. **Ólafur Ögmundarson:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Bryndís Eva Birgisdóttir:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Þórhallur Ingi Halldórsson:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A

Table A.1
Amount in grams per day from different food groups in the three dietary guidelines

	Eat-Lancet	Danish FBDGs	NNR23
Dairy foods	≤500	≤250	≥350 and ≤ 500
Red meat	≤28		≤50
White meat	≤58		
All meat and meat products		≤50	
Fish	100	50	~40–65
Vegetables	600	300	400
Fruits	300	300	400
Whole grains	~230	75	90
Nuts	75	30	20–30
Legumes	100	100	

EAT-Lancet planetary health diet shows the upper ranges.

Table A.2
GHG emissions for the demographic information based on the Icelandic National Dietary Survey 2019–2021.

	Danish CONCITO	US dataFIELD	French AGRIBALYSE
	Mean (SD) [a,b] kg CO_2-eq/day		
Sex			
Female	5.25 (3.81)	5.21 (2.89)	5.16 (2.29)
Male	7.53 (5.51)	7.12 (4.08)	7.08 (3.16)
Age (years)			
18-39	6.46 (5.20)	6.15 (4.08)	6.05 (3.46)
40-59	6.49 (5.22)	6.09 (3.20)	6.17 (2.69)
60-80	6.07 (3.94)	6.15 (3.71)	6.00 (2.61)
Education			
Primary School	5.29 (3.05)	5.32 (2.74)	5.36 (2.32)
Upper secondary school	6.62 (5.24)	6.45 (3.77)	6.41 (3.11)
University degree	6.55 (5.01)	6.23 (3.85)	6.13 (2.92)
Other	6.41 (5.13)	6.01 (3.29)	6.04 (2.89)
Smoking			
Yes	5.63 (3.56)	5.6 (2.77)	5.91 (2.85)
No	6.42 (4.94)	6.18 (3.70)	6.10 (2.91)
BMI (kg/m^2)			
<18.5	7.56 (4.92)	6.08 (3.05)	6.75 (2.20)
18.6–24.99	6.25 (4.41)	6.14 (3.93)	6.05 (2.86)
25–29.99	6.43 (5.38)	6.04 (3.40)	6.02 (2.88)
>30	6.42 (4.59)	6.32 (3.66)	6.28 (3.07)
Residence			
Capital Area	6.28 (4.73)	6.02 (3.28)	6.03 (2.77)
Rural Area	6.47 (5.03)	6.31 (4.18)	6.16 (3.13)

Abbreviations: GHG – greenhouse gas. BMI - Body Mass Index.

[a] Using Kruskal-Wallis *H* test, comparison revealed no significant differences between the three databases for all variables ($p = 0.05$).

[b] Using Mann Whitney *U* test, comparison for sex revealed a significant difference between female and male in all three databases. All other variables were insignificant. Using Kruskal-Wallis H test for categorical variables with more than two groups also revealed no significant difference for all variables in the three databases.

Table A.3
Dietary GHG emissions (kg CO_2-eq/day) among participants in the Icelandic National Dietary Survey 2019–2021. Mean (SD) consumption and GHG emissions for food groups, data are shown for three databases. The values shown for the Danish and US databases are based on their original system boundaries. That is without adjustment for food loss, which is included in the French database.

Food groups	Consumption	**Danish** ***CONCITO***	**US** ***dataFIELD***	**French** ***AGRIBALYSE***
	Mean (SD) g/day	Mean (SD)[a] kg CO_2-eq/day		
Beef and veal	25 (41)	1.57 (3.77)	0.91 (1.57)	0.97 (1.66)
Lamb and mutton	24 (47)	0.88 (1.72)	1.11 (2.18)	1.03 (1.99)
Pork and pig	24 (36)	0.20 (0.32)	0.24 (0.35)	0.27 (0.43)
Other red and processed meat	7 (25)	0.19 (0.77)	0.23 (0.83)	0.09 (0.42)
Poultry and eggs	55 (62)	0.15 (0.19)	0.26 (0.30)	0.25 (0.31)
Seafood	44 (57)	0.57 (0.75)	0.18 (0.38)	0.54 (0.88)
Dairy products	312 (256)	0.61 (0.37)	0.96 (0.86)	0.90 (0.62)
Fruits	91 (104)	0.10 (0.11)	0.04 (0.05)	0.11 (0.13)
Cereals	168 (104)	0.19 (0.13)	0.15 (0.11)	0.30 (0.23)
Other plant-based sources [b]	184 (122)	0.18 (0.16)	0.11 (0.09)	0.22 (0.17)
Beverages	1630 (734)	0.55 (0.46)	0.79 (1.10)	0.82 (0.57)
All other foods	150 (113)	0.39 (0.26)	0.55 (0.65)	0.57 (0.55)
Total GHG emissions		5.57 (4.25)	5.54 (3.27)	6.08 (2.91)

Abbreviations: CO_2-eq. - carbon dioxide equivalent. GHG emissions - greenhouse gas emissions.

The Danish *CONCITO* database launched in 2021 (The Big Climate Database, 2021).

US *dataFIELD* (database of Food Impacts on the Environment for Linking to Diets) launched in 2017 (dataFIELD, 2018).

The French *AGRIBALYSE* database launched in 2013 (AGRIBALYSE, 2020).

[a] Using Kruskal-Wallis *H* test, comparison revealed no significant differences between the three databases for the food groups Beef and veal, Lamb and mutton, Pork and pig, and Other red and processed meat. For all other food groups, the three databases were significantly different ($p < 0.05$).

[b] The food group "Other plant-based sources" excludes fruits and cereals.

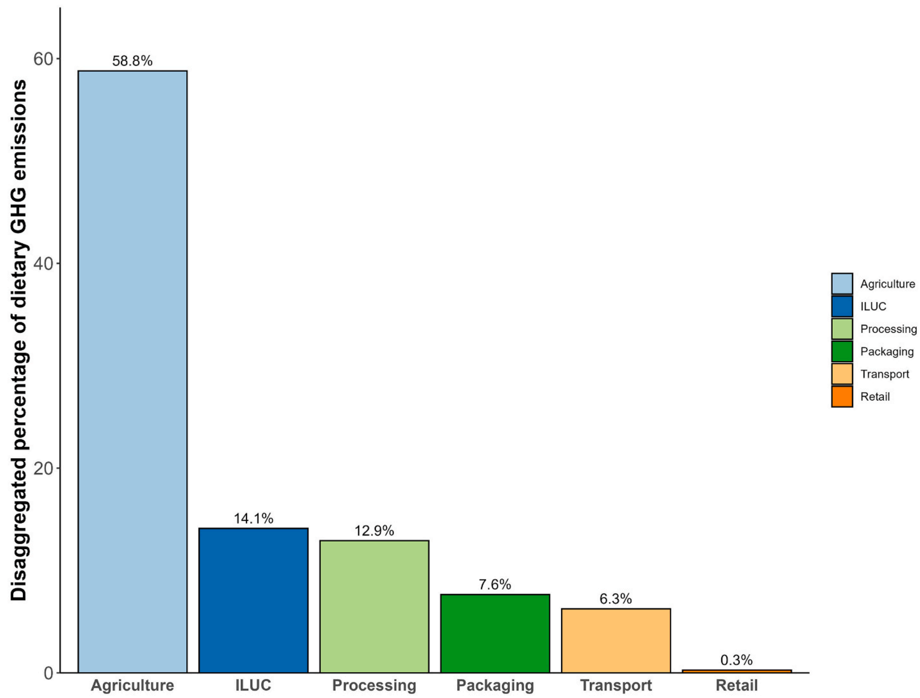

Fig. B.1. Disaggregated distribution of the total dietary GHG emissions for the participants in the 2020–2021 National Dietary Survey, across different sectors in the food supply chain. Analyzed using the Danish *CONCITO* database.

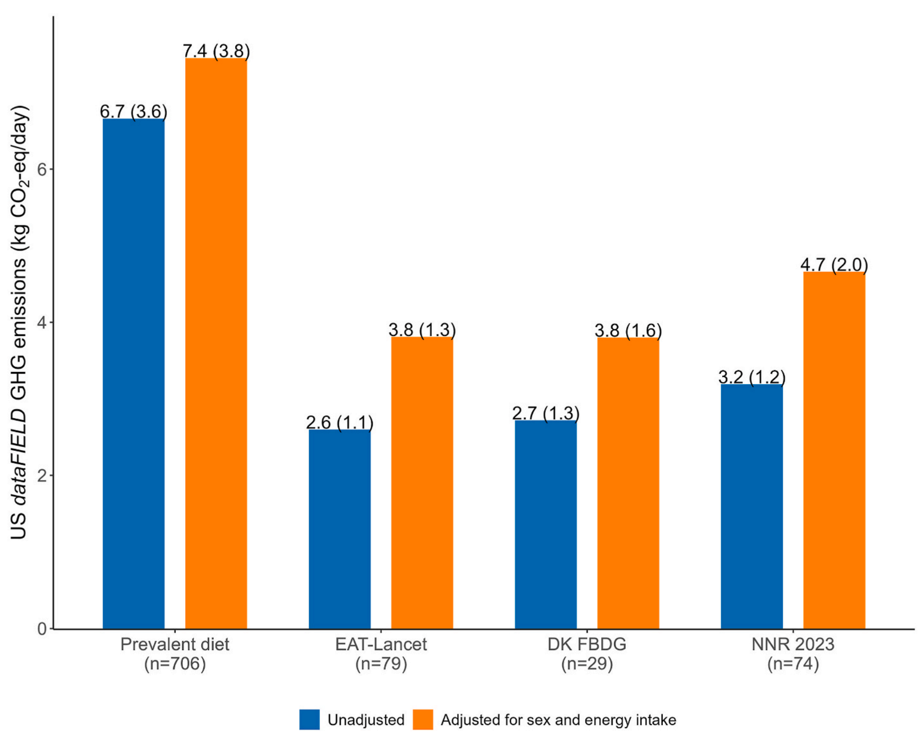

Fig. B.2. Total dietary GHG emissions, in kg CO_2-eq/day, for survey participants whose consumption was within or outside the ranges set for meat and dairy products in the prevalent diet (outside ranges), EAT-Lancet (Willett et al., 2019), Danish FBDGs (Danish Veterinary and Food Administration, 2021); NNR 2023 dietary recommendations (Blomhoff et al., 2023). These estimates are based on the US *dataFIELD* database. The mean (standard deviation) is reported above each bar and the results are shown as unadjusted and adjusted for sex and estimated energy requirement for each participant.

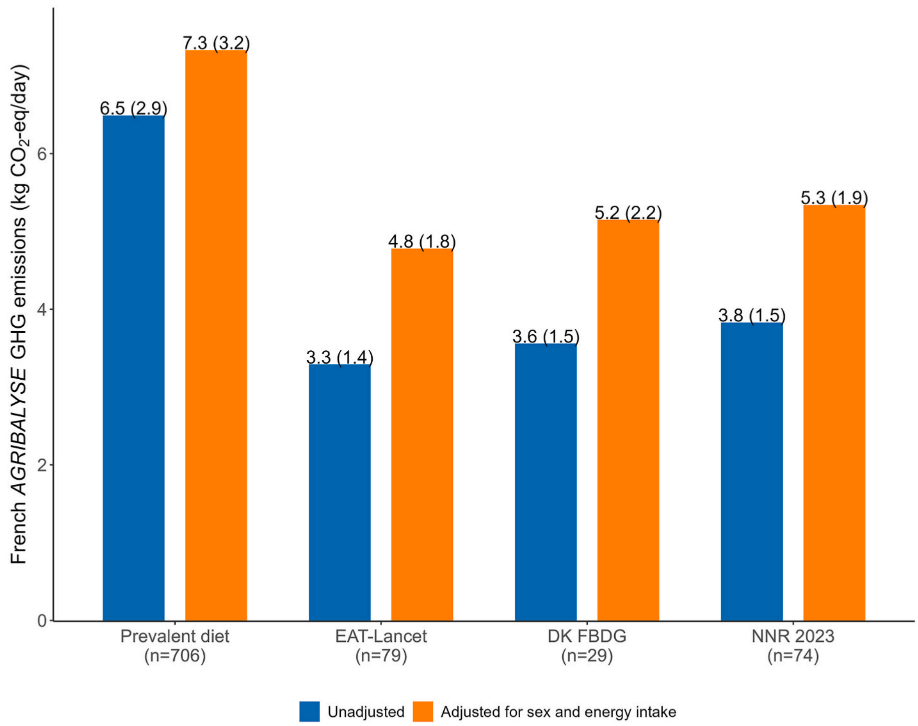

Fig. B.3. Total dietary GHG emissions, in kg CO_2-eq/day, for survey participants whose consumption was within or outside the ranges set for meat and dairy products in the prevalent diet (outside ranges), EAT-Lancet (Willett et al., 2019), Danish FBDGs (Danish Veterinary and Food Administration, 2021); NNR 2023 dietary recommendations (Blomhoff et al., 2023). These estimates are based on the French *AGRIBALYSE* database. The mean (standard deviation) is reported above each bar and the results are shown as unadjusted and adjusted for sex and estimated energy requirement for each participant.

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