Sustainable Production and Consumption 51 (2024) 584–598

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Contribution of ultra-processed food and animal-plant protein intake ratio to the environmental impact of Belgian diets

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A R T I C L E I N F O

Editor: Dr Jasmina Burek

Keywords:
Life cycle assessment
Environmental impact
Belgium
Diet
Protein
Ultra-processed food

A B S T R A C T

There is growing concern about the various impacts of food consumption, both on human and planetary health. Given the context-specific nature of consumption patterns, evaluating their national-level impacts is crucial for proactive policy development. This research aims to evaluate the environmental impact of current Belgian diets, with particular attention to the contribution of food groups, ultra-processed foods (UPF), and the animal-to-plant protein ratio. The methodology consists of three key stages. Firstly, the Belgian diet was summarised, based on data from the Belgian National Food Consumption Survey 2014/2015. Secondly, the origin of the most frequently consumed foods was traced using trade databases. Finally, a cradle-to-grave life cycle assessment was conducted to determine the impact of Belgian diets on climate change, water use, land use, and fossil resource scarcity. In this third step, an iterative procedure for selecting the food items to be included in the study was performed. The iterative approach resulted in the inclusion of 227 food items in the analysis. The results indicate greenhouse gas (GHG) emissions of 4.4 [4.27–4.54] kg CO_2-equivalent per person per day. Red meat (35 %), beverages (16 %), dairy products (12 %) and snacks (10 %) are identified as primary contributors to climate change. Similar results were observed for land use impacts. Water use and fossil resource scarcity exhibited different trends, with beverages being the most impactful food group. Moreover, UPF account for 50 % of the total climate change and land use impacts, with a linear relationship observed between increased UPF consumption and GHG emissions and land use. A similar linear trend is observed between the ratio of animal-to-plant protein intake and both climate change and land use impact categories. A shift from the current protein ratio to a ratio of 40/60, as suggested in the Flemish Green Deal Protein Shift has been shown to result in a reduction in GHG emissions of the diet by 29 %. This study emphasises the need to target the consumption of high-impact foods such as UPF and animal-based products. Future research will investigate the relationship between environmental and health impacts.

1. Introduction

Food consumption is one of the most resource-intensive activities and a major driver of environmental impacts (Notarnicola et al., 2017). Food systems account for about 26 % of total greenhouse gas (GHG) emissions, while half of the world's habitable land is used for agriculture (Poore and Nemecek, 2018). In addition, agriculture is responsible for about 70 % of global freshwater withdrawals (FAO, 2021). Our food production methods and dietary habits are crucial to address pressing environmental challenges. In 2019, the EAT Lancet report, prepared by a commission of 18 co-authors from 16 countries representing various fields of public health, agriculture, political sciences, and environmental sustainability, identified a set of boundaries for food systems that must not be exceeded in order to remain within the safe operating space. The boundary established for climate change limits the annual emission to 5Gt CO_2 equivalent (CO_2-eq) for the global food system. Staying within this boundary requires a shift in production methods and diets (Willett et al., 2019).

Historically, in the 1950s and 1960s, high-income regions

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https://doi.org/10.1016/j.spc.2024.10.008
Received 2 July 2024; Received in revised form 4 October 2024; Accepted 11 October 2024
Available online 14 October 2024

Abbreviations

GHG	Greenhouse gas
UPF	Ultra-processed foods
LCA	Life cycle assessment
LCI	Life cycle inventory
CO_2-eq	CO_2 equivalent
Crop-eq	Crop equivalent
Oil-eq	Oil equivalent
Q1	Quintile 1
Q5	Quintile 5

experienced a 'dietary transition' towards greater consumption of animal-based foods, often at the expense of plant-based foods (Popkin, 2006). This shift is reflected in the high and excessive consumption of animal protein in these regions nowadays (Afshin et al., 2019). This trend is also observed in Belgium, where the majority of the population exceeds dietary recommendations for protein and meat consumption (Bel et al., 2019). The increased consumption of animal-based foods has led to the intensification of livestock production, putting considerable pressure on land use, water use, greenhouse gas emissions and nitrogen and phosphorus cycles (Bouwman et al., 2013). This underlines the necessity for a shift towards more plant-based diets, which are beneficial for both the environment and human health. This need for a protein shift is illustrated in Belgium by initiatives such as the Flemish Green Deal Protein Shift, launched in Flanders in 2021, which aims to shift the animal-to-plant protein ratio from 60/40 to 40/60 by 2030 (Omgeving Vlaanderen, 2021). The overarching objective of this shift is to promote more sustainable and healthier diets. However, the precise environmental implications of this transition remain to be fully identified.

A further contemporary challenge is the industrialisation of the food system and the associated increase in the consumption of ultra-processed foods (UPF). These products, which are high in salt, fat, and sugar, pose significant public health risks as major contributors to non-communicable diseases (Willett et al., 2019). Recently, there has been a growing interest in the environmental implications of these foods, highlighting the importance of UPF in environmental degradation across various countries (Anastasiou et al., 2022). No data were found regarding the environmental implications of UPF in the context of Belgian food consumption.

Some studies on the environmental impact of diets have been conducted at the national level (e.g. for Denmark (Bruno et al., 2019), Japan (Sugimoto et al., 2020), France, Italy, and the Czech Republic (Mertens et al., 2019), the Netherlands (Vellinga et al., 2019) and Brazil (Travassos et al., 2020)). Yet, no scientific peer-reviewed publications could be found on Belgian diets. To date, there is only one report on the subject, carried out by the WWF (WWF, 2021). The analysis, conducted at the household level, assessed the impact of the Belgian diets on categories of climate change, land use change and biodiversity (damage to ecosystems). Although the report analysed 175 food items, no clear rationale was provided for their final selection. Furthermore, the research employed aggregated Belgian food consumption data, retrieved from the EFSA Comprehensive Food Consumption Database. Although this study offers some first insights, there remain questions regarding the detailed methodology for the environmental impact assessment.

The present study aims to address these shortcomings by examining the environmental impact of Belgian dietary patterns. Analyses are carried out by age group and sex, as well as by food group. The study places a novel emphasis on the ratio of animal-to-plant protein, examining the implications of a shift, as suggested by the Flemish Green Deal Protein Shift. Furthermore, the study will evaluate the environmental implications of the degree of food processing. This research forms part of a national project (SUSFOODBEL) with the objective of formulating policy recommendations at the national level that can enhance food environments and facilitate the transition towards more sustainable and healthy diets. The present analysis is of significant importance for informing national policy and incorporating sustainability indicators into dietary recommendations.

2. Literature review

In recent years, it has been highlighted that dietary change is necessary and that a production change alone is insufficient to mitigate environmental impacts (Poore and Nemecek, 2018). In this context, a considerable number of studies have been conducted to evaluate the environmental impact of different diets (Castañé and Antón, 2017; Chai et al., 2019; Moberg et al., 2020). Various studies have demonstrated that there is a positive correlation between the consumption of animal-based foods (meat and dairy) and environmental impacts (Springmann et al., 2018; Vellinga et al., 2019). Conversely, plant-based diets have been shown to have a lower net impact (Fresán and Sabaté, 2019; Svanes et al., 2024). A recent scoping review by Ferrari et al. (2022) evaluated the health outcomes and environmental impact associated with animal and plant-based protein sources. The study concludes that plant protein consumption offers significant health benefits, particularly in reducing the risk of cardiovascular disease, while also demonstrating greater environmental benefits, compared with animal protein consumption (Ferrari et al., 2022). Therefore, the protein shift has gained traction in recent years as a potential way to reduce the environmental impacts associated with food consumption (Aidoo et al., 2023; Duluins and Baret, 2024; Heerschop et al., 2023). The animal-to-plant protein ratio is frequently employed to characterise different diets, for health purposes (Montenegro-Bethancourt et al., 2015; Azemati et al., 2021; Vieux et al., 2022) and more recently, for environmental ones (Fouillet et al., 2023; Simon et al., 2024). In their study, Fouillet et al. (2023) identified a positive correlation between the ratio of animal-to-plant protein in French diets and GHG emissions. Similar trends were observed for land use and fossil resource scarcity although a negative association was found for water use. Overall, the single score, which accounted for 16 environmental indicators, decreased from 37 % with a shift of the protein ratio from the current one (approximately 30/70) to 70/30 (Fouillet et al., 2023). Another recent study shows that a shift in the ratio (towards 40/60) can lead to significant reductions in environmental impacts (namely climate change and land use), even more so within a European circular food system approach (Simon et al., 2024). However, in light of the findings of Fouillet et al. (2023), which indicate an increase in water use as the ratio of animal to plant protein decreases, future studies should consider water use in order to provide a more comprehensive assessment of the environmental impacts. Both studies showed that a 40/60 ratio does not lead to nutrient deficiencies, as is often the case with larger reductions (e.g. vitamin B12), even when protein intake is reduced to recommended levels. This narrative (protein shift) has been used in strategies for the transition to healthier and more sustainable diets in Belgium (Omgeving Vlaanderen, 2021) and the Netherlands (Raad voor de leefomgeving en infrastructuur, 2018). Therefore, one of the aims of this study is to investigate the potential environmental consequences of changing the protein ratio in Belgium, also in terms of water use, and to compare the results with the studies mentioned above. This could provide a basis for more robust policy initiatives and future targets.

Besides animal and plant protein consumption, the level of food processing in diets is receiving increasing attention. Globally, the consumption of UPF has increased in recent years and these products now constitute a substantial portion of the diet in many countries (Elizabeth et al., 2020). The NOVA classification was developed by Monteiro et al. (2018) and is used to classify foods according to the degree and purpose of processing. It defines UPFs as food products made from a combination of ingredients, often exclusively used in industry (e.g., as additives, preservatives, sweeteners) and produced through a range of industrial methods and processes. This encompasses carbonated drinks, packaged snacks and pre-prepared dishes among other items. Formulated to be convenient, palatable and long-lasting, these products often bear little resemblance to whole foods (Monteiro et al., 2018). The impact of UPF on human health is well documented, with evidence indicating its association with obesity and overweight, type two diabetes and certain cancers (Lane et al., 2024; Shu et al., 2023; Suksatan et al., 2022). A recent study has also highlighted the association between plant-sourced UPF and elevated mortality, underlining the importance of considering the level of processing in dietary recommendations (Rauber et al., 2024). In contrast, the related environmental impact has only recently gained attention (Anastasiou et al., 2022; García et al., 2023; Garzillo et al., 2022; Kesse-Guyot et al., 2023). However, studies on the relationship between UPF consumption and environmental impact have yielded inconclusive results. Some suggest higher water use as UPF consumption increases (+10 % between quintile 1 (Q1) and quintile 5 (Q5) in Brazil) (Garzillo et al., 2022), while others have found the opposite (García et al., 2023; Kesse-Guyot et al., 2023; Vellinga et al., 2022), with for example, −7 % between lower and higher UPF consumers (between Q1 and Q5) in the French study. Similarly, a number of studies have demonstrated a link between UPF consumption and climate change (García et al., 2023; Kesse-Guyot et al., 2023; Vellinga et al., 2022), with for example an increase of 15 % between Q1 and Q5 in the French study, while others could not confirm such correlation (no significative linear trend observed across quintiles in Brazil) (Garzillo et al., 2022). The consumption rates and environmental impact of UPF vary considerably across countries. For example, in France and the Netherlands, UPF accounts for 24 % and 45 % of total GHG emissions of food, respectively (Kesse-Guyot et al., 2023; Vellinga et al., 2022). The studies on this topic highlight the methodological limitations of current research and suggest avenues for future investigation. They emphasize the need for more research on the environmental impact of UPF consumption, particularly in diverse settings and contexts (Kesse-Guyot et al., 2023), with a focus on a range of environmental impacts beyond climate change (Anastasiou et al., 2022; Garzillo et al., 2022), and across the entire food system (Anastasiou et al., 2022). Furthermore, a gap exists in the current literature on this specific topic, in the context of Belgium, which this study seeks to address.

To gain an understanding of the environmental implications of dietary choices, it is necessary to employ robust methodologies, such as Life Cycle Assessment (LCA), which takes into account all steps of the food supply chain, from production to consumption and end-of-life of food loss and waste (ISO, 2006a). This method is the most commonly used method to assess the environmental impact of food products (Jones et al., 2016). In particular, the origin of consumed food is a crucial factor when calculating dietary emissions. This is not only due to international transport, which usually represents a relatively minor source of emissions (Weber and Matthews, 2008), except if goods are transported by plane (Sim et al., 2007). Rather, it is primarily due to the diverse agricultural production systems and methods employed in different countries, resulting in varying emission intensities (Carlson et al., 2017). Dietary environmental impact assessment can be conducted by linking representative consumption data, such as national consumption surveys to life cycle inventory databases. For instance, in Belgium, the most recent National Food Consumption Survey was conducted between 2014 and 2015 and included around 1500 foods and >3000 participants, which was estimated to be representative of the Belgian population's consumption patterns (Bel et al., 2016). The combination of LCA with national consumption data has been employed in a few other countries (Mertens et al., 2019; Sugimoto et al., 2020; Vellinga et al., 2019). In these studies, it is common practice to evaluate only a subset of food items due to resource constraints. The assessment of the remaining food items of the diet and the selection of the number of foods to be included is based on expert judgment or is unclear. No uniform methodology was identified. The present study therefore proposes a systematic approach to the selection of food items and the extrapolation of results in order to calculate the environmental impact of the entire diet for all individuals included in the food consumption survey.

In light of these considerations, this research aims to address several knowledge gaps by assessing the environmental impact of Belgian diets utilising LCA methodology. First, a systematic way of selecting food items for dietary assessment is developed. The study is based on detailed consumption data from the Belgian National Food Consumption Survey 2014/2015 and incorporates the Belgian food supply chain into the modelling process. Then, the environmental impact of the Belgian diet is analysed, after which two critical aspects of the diet are analysed. The first aspect to be considered is the current landscape of protein type consumption in Belgium, with the idea to explore the potential environmental implications of a shift. The second aspect is to gain understanding of the importance of the level of food processing in Belgium in assessing the environmental impact of diets.

3. Methods

In this study, the environmental impact of the average Belgian diet was investigated. The overall approach is illustrated in Fig. 1, and further detailed in the following sections. Briefly, the Belgian diet was defined using data from the Belgian National Food Consumption Survey 2014/2015 (Bel et al., 2016), focusing on frequently consumed food items (Section 3.1). Trade databases were utilized to account for the origin of these frequently consumed foods (Section 3.2). By combining data on the quantity of food consumed and the environmental impact per food, the total environmental impact of the average Belgian diet could be determined (Section 3.3). The final selection of food items to be included in the analysis was made in an iterative process. Initially, 50 % of the observations were included in each food group, after which the environmental impact was computed and extrapolated to reach 100 % of energy intake. This process was repeated with each time the inclusion of +5 % points of observations in each food group. The procedure was terminated when the extrapolated result remained constant, i.e., till the point where further adding food items in the assessment had no more added value to estimate the total environmental impact of the Belgian diet. The data processing, linking of data sources and statistical analyses, were performed utilising the SAS 9.4 software.

3.1. Average Belgian diet

3.1.1. Belgian National Food Consumption Survey

Food consumption data were derived from the Belgian National Food Consumption Survey conducted in 2014–2015 by the Belgian Institute of Public Health (Sciensano), which provides the most up-to-date information on food consumption in Belgium. A representative sample of children and adults aged between 3 and 64 years were selected using a multi-stage stratified sampling procedure, resulting in a final sample of 3146 participants (992 children (3–9 years), 928 adolescents (10–17 years) and 1226 adults (18–64 years)). The gender distribution was approximately 50/50. General information on socio-demographic characteristics (such as place of residence and level of education), lifestyle and level of physical activity was also collected. A summary of the food consumption data collection is presented in Appendix A; the full data collection methods are described by Bel et al. (2016).

3.1.2. Data processing to model the average Belgian diet

The Belgian Food Consumption Survey covers >1500 different food items (Bel et al., 2016). To calculate the environmental impact, some food items were aggregated into a more general food item. This was done considering the similarity between the food items and based on the food items available in the Agribalyse v3 database (e.g. raw ham 'farmers', raw ham 'Ardeense', raw ham 'Parma', raw ham 'Bayonne' were aggregated to 'raw ham'). The aggregation resulted in a total of 1140 food products. An overview of aggregation can be found in Appendix E, Table S1. In addition to this aggregation, a number of most

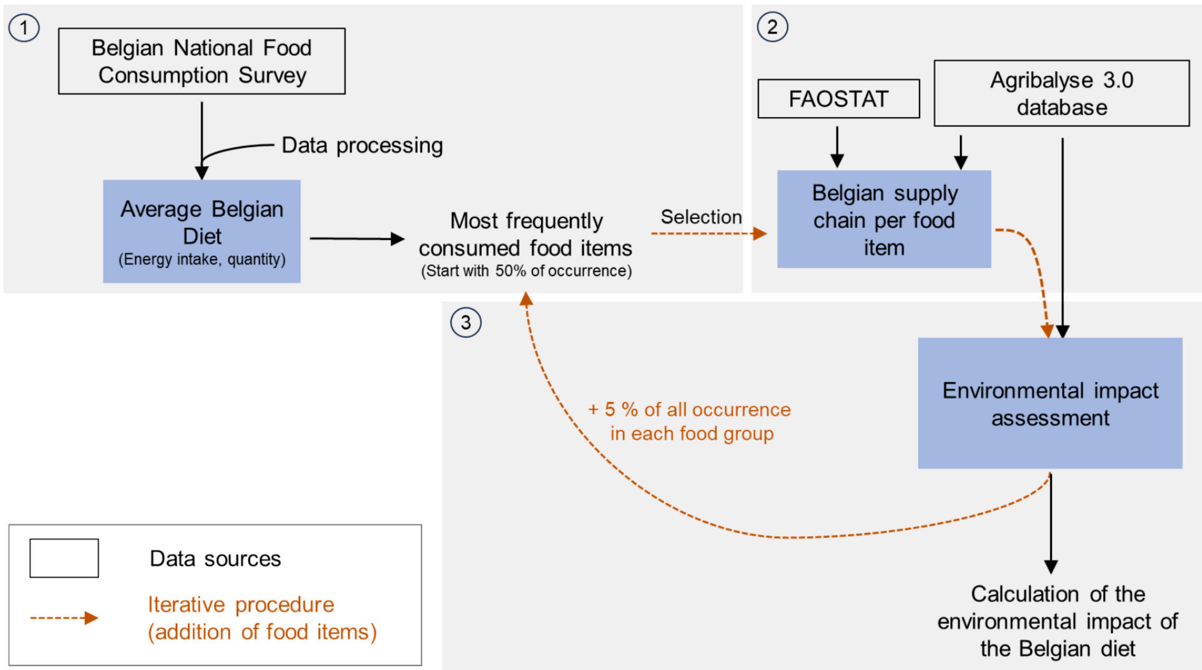

Fig. 1. Methodological approach for defining the environmental impact of the average Belgian diet. (1), (2) and (3) refer to the main stages of the methodology.

frequently consumed food items was selected to calculate the environmental impacts. An iterative process was used to add an additional set of most frequently consumed food items. The selection procedure is explained later in Section 3.3.2.

A classification of the type of protein contained in each food was made. The total protein content of foods from exclusively animal sources was designated as animal protein. The total protein content of exclusively plant-origin foods was considered plant-based protein. For foods of mixed origin (containing both animal and vegetable protein), the total protein content was classified as mixed protein (e.g., cakes, and sauces). This classification was already used in the study by Pasiakos et al. (2015). Based on this classification, the proportions of plant, animal and mixed protein in the Belgian diet were calculated.

All consumed foods and ingredients were also classified according to the NOVA classification, as previously described by Vandevijvere et al. (2019). Further details regarding the NOVA classification and its application in this study can be found in Appendix B. Alcoholic beverages have not been categorised according to the NOVA classification and were kept as a separate group.

3.1.3. Computation of the average Belgian diet

The Belgian National Food Consumption Survey provides consumption data for two days per person. The two-day consumption records were averaged for each individual and then a weighted average was calculated for the whole population. Individual weights were assigned to the sample, taking into account factors such as age, gender, season, day of the week of the interview, and province in order to provide representative results for the Belgian population. In addition, this stage involved the calculation of the individual quantity consumed and energy intake.

3.2. Belgian supply chain per food item

Once the average diet had been defined, the Belgian supply chain was identified for each of the most frequently consumed food items ((2) Fig. 1). A dataset was created containing information on the trade and domestic production of the food consumed in Belgium (consumption mix) and the transport required.

The term ‘consumption mix’ refers to the breakdown of food consumed in a country according to the country of production. To assess the environmental impact of the Belgian diet, the origin of the consumed food items, and thus international trade, were considered. For this purpose, a Belgian consumption mix dataset was developed analogous to the protocol used in the Agribalyse v3 database to analyse the French consumption mix (Asselin-Balençon et al., 2022).

Consumption breakdown per country of origin was determined according to Eqs. (1) and (2), with all quantities being expressed in mass (tonnes (t)), and averaged over five years (2017–2021):

$$Origin\ ratio_{BE} = \frac{Production_{BE}}{Production_{BE} + \sum_{i=1}^{n} Imports_{From country\ i\ to\ BE}} \tag{1}$$

$$Origin\ ratio_{country\ i} = \frac{Imports_{From country\ i\ to\ BE}}{Production_{BE} + \sum_{i=1}^{n} Imports_{From country\ i\ to\ BE}} \tag{2}$$

$Production_{BE}$ refers to total Belgian production (t); $Imports_{From\ country\ i\ to\ BE}$ are the total imports from country i to Belgium (t); Origin $ratio_{BE}$ is the proportion of total Belgian consumption produced in Belgium and Origin $ratio_{country\ i}$ equals the proportion of total Belgian consumption produced in country i.

FAOSTAT data were used to determine the share of consumption related to national production (FAO, 2023a) and imports from other countries (FAO, 2023b).

Following the Agribalyse methodology and based on expert knowledge, several assumptions were made to construct this consumption mix dataset:

- It was assumed that the exclusion of exports leads to the most accurate estimation of the origin mix. Taking exports into account can lead to odd results where exports are higher than domestic production, which is not accurate according to expert judgment (Asselin-Balençon et al., 2022).
- Food items with a Belgian origin ratio higher than 80 % were assumed to be 100 % produced in Belgium (e.g., red meat and milk)
- Only the four largest importers of each food product were taken into account if they represented at least 70 % by weight of the food

supply, otherwise, the next largest importers were added until this 70 % was reached. This was then normalised to 100 %.

Appendix E, Table S2 contains the consumption mix dataset with information on the origin of the raw foods consumed in Belgium.

Transport, from agricultural production to processing, was defined according to the consumption mix. Only transport of food to Belgium was considered, excluding transport within Belgium and assuming that the processing country was always Belgium. Refrigerated transport was considered at different stages of the food supply chain for certain foods (Appendix C, Table C1). Data on the 5-year average modal split from EuroStat (Eurostat, 2023) were used. This modal split divides transport into five different modes (road, rail, inland waterways, sea and air). For intra-European trade, we assumed that there was no sea and no air transport (Appendix C, Table C2). Transport distances were estimated using Google Maps, Google Earth and Routescanner.

3.3. Environmental impact assessment

The Belgian consumption mix dataset and defined transport distances and means were then used to determine the environmental impact of the most consumed food items ((3) Fig. 1).

3.3.1. Life cycle assessment

LCA, according to the ISO standards 14,040 (ISO, 2006a, 2006b), was used to assess the environmental impact of the current Belgian diet (including food and beverages). According to ISO 14040, four stages are considered: (1) goal and scope, (2) life cycle inventory, (3) impact assessment and (4) interpretation (ISO, 2006a).

The functional unit corresponded to the daily dietary intake of an average Belgian. The studied population was aged between 3 and 64 years, with both males and females included. The system boundary was 'from cradle to grave' and is shown in Fig. 2. Food loss and waste were considered at different stages of the life cycle, except at consumer stage. Information for the latter was not available in Agribalyse and no Belgian database on food waste in quantitative form was found. Transport was considered at each stage except between retailer and consumer's home.

The French database Agribalyse v3 was used for the life cycle inventory (LCI) data. The database contains life cycle inventories for around 2500 products consumed in France. In the absence of a Belgian database, Agribalyse was adapted with the Belgian consumption mix to be as representative as possible for the Belgian context. The methodology is consistent with the prevailing international guidelines for LCA: ISO 14040 and PEF. The database is transparent and based on unit processes, with data available from the beginning to the end of the food production cycle. ecoinvent 3.8 and WFLDB are integrated into Agribalyse, mainly for unavailable food processes (WFLDB) or as a background database (ecoinvent) for logistics (e.g. transport, electricity) and imported production. Further details regarding the specific processes used for transport can be found in Appendix C. A decision tree (Appendix D, Fig. S1) was followed to determine which datasets were used regarding the origin of food items. When choosing a production method, the national average is always preferred, followed by conventional and then organic cultivation. LCI datasets were not available for 17 food products. In these cases, proxies based on biological proximity, similarity of farming methods, and farming environment were used. All proxies used are listed in Appendix E, Table S3. Several additional assumptions were made:

- For certain foods, different cooking methods could be used (e.g. potatoes, boiled, fried, baked, etc.). An average of the different methods was taken.
- If the exact food item was not specified in the consumption survey (e.g. fish), the average of known fish with available datasets was used (e.g. the average of sole, salmon and cod).
- If two different datasets in Agribalyse v3 corresponded to the description of one food product, the average of the two datasets was used (e.g. for chocolate biscuits, an average of biscuits with chocolate filling and biscuits with chocolate coating).

The specific averages used can be found in Appendix E, Table S4. The majority of the allocation used throughout the Agribalyse database is economic, in line with existing processes (ecoinvent). It should be noted that there are a few exceptions to this rule. For instance, the modelling for dairy husbandry uses biophysical allocation, while cheese production uses mass allocation. Additionally, if the is processing aimed at obtaining the edible part of the product (such as peeling, pitting and unshelling), all impacts were allocated to the edible part (Asselin-Balençon et al., 2022).

The environmental impact was calculated using the ReCiPe 2016 Midpoint (H) V1.08/World (2010) H method and Simapro software version 9.5. Climate change was assessed in terms of GHG emissions, expressed in kilograms (kg) of carbon dioxide equivalent (CO_2-eq). Water use was calculated in cubic metres (m^3) and according to water consumption and depletion in specific regions, considering scarcity (use of water requirement ratios). Land use (m^2 crop equivalent (crop-eq)) refers to the relative species loss caused by a particular type of land use. Fossil resource scarcity was expressed in kg oil-equivalent (oil-eq), which allows different fossil fuels to be compared in terms of the energy content equivalent to 1 kg of oil. There was a focus on climate change, land use, and water use as they are key impact categories for food production and commonly used in dietary environmental impact assessments (Chai et al., 2019; García et al., 2023; Silva et al., 2021). Fossil resource use or scarcity, has recently been included in more studies, notably because of its importance in food processing (Fouillet et al., 2023; García et al., 2023; Kesse-Guyot et al., 2023).

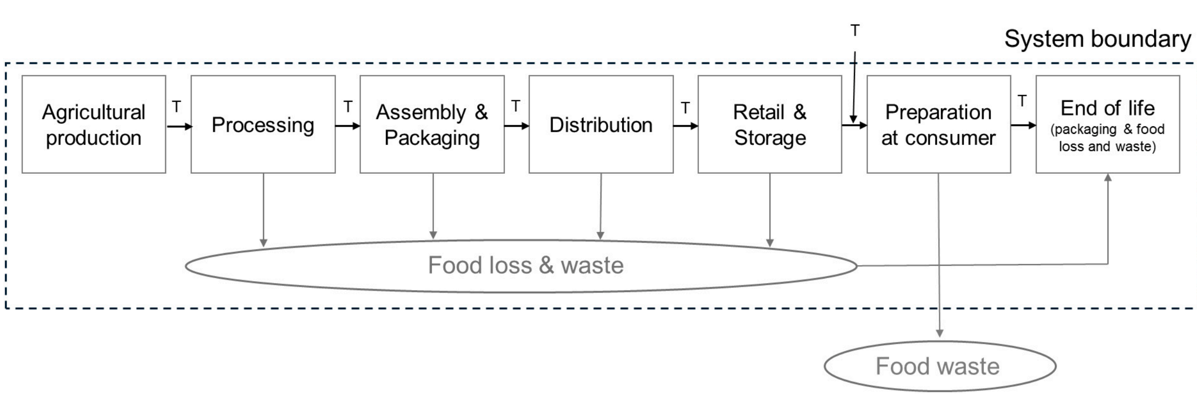

Fig. 2. System boundaries of the LCA of each food item. T means transport.

3.3.2. Iterative procedure to determine the environmental impact of the average Belgian diet

In line with several other studies (Hollander et al., 2016; Masset et al., 2014; Vellinga et al., 2019), a selection of food items was made based on frequency of consumption to estimate the average environmental impact of the diet. To make this selection, an iterative approach was developed. Additionally, the concept of a food group was employed. A food group can be defined as "*a category of foods that share similar nutritional properties, similar origin of production, similar marketing characteristics, or all three*" (Montagnese et al., 2015). Within each food group, the food items were ranked by the most frequently consumed (i.e., consumed by the largest number of people). Food items were then systematically selected until they collectively represented 50 % of the total observations within the food group (e.g. apple, banana and tangerine represent 50 % of all observations in the fruit food group). Observations refers to the number of times food items have been consumed within each food group, in the total population. For each survey participant, the environmental impact of the selected foods was evaluated. This result was then extrapolated with the percentage of energy intake non-included, to account for the non-included food items. The average environmental impact for the entire population was then computed. An incremental methodology was applied, repeating the process with 5 %-point increments of the total observations of food items in the respective food group, thereby increasing the number of food items included in the analysis gradually. The aim was to identify where the average extrapolated footprint for the entire population stabilised, indicating a horizontal asymptote where the addition of food items no longer changes the footprint. For that purpose, two extrapolation approaches were then explored to obtain the average environmental impact of the whole diet. A first approach was focused on extrapolating per food groups. The environmental impact for each individual was aggregated by food group before extrapolation, as foods within the same group typically exhibit similar environmental impacts. The average for the total population was then calculated. However, this aggregation prevented the analysis of data by quintile, which is conducted in the subsequent sections of this article (Sections 4.2.4 and 4.2.3). An illustration of the result is presented in Appendix D, Fig. S2. Therefore, a second extrapolation method was considered whereby extrapolation was conducted at the level of each participant. The environmental impact associated with each participant was extrapolated to include the non-included energy intake. The average for the total population was then calculated. This second method permitted the calculation of environmental impact data for each participant, thereby enabling the analysis of the population distribution and quintile analysis.

3.3.3. Statistical analysis

To analyse the contribution of protein type consumption to the environmental impact of the Belgian diet, the ratio of animal to plant protein was calculated. The adult population was then divided into five quintiles according to this ratio. Q1 has the lowest ratio and Q5 has the highest. Linear regression analyses were performed to assess associations between the quintile of protein ratio and environmental impacts. To analyse the contribution of UPF consumption to the environmental impact, the adult population was divided into five quintiles according to the percentage of energy intake from UPF. Q1 has the lowest percentage of energy intake from UPF and Q5 has the highest. Linear regression analyses were performed to assess relations between the quintile of UPF and the environmental impacts. For both the analysis of the impact of UPF and protein type, the total energy intake, total amount consumed, protein intake and age were also integrated into the analysis as covariates.

4. Results and discussion

4.1. Introduction of an iterative procedure for dietary environmental impact assessment of the Belgian diet

Two distinct extrapolation methodologies were employed, one employing individual-level extrapolation and the other employing extrapolation at the food group level. Between these two, the difference in the total climate change impact of the average Belgian diet is only differing by 3.2 %. This suggests that the results remain fairly accurate regardless of the extrapolation method used. The result of the iterative process with individual-level extrapolation for the impact of climate change is presented in Fig. 3. The figure presents the impact on climate change linked with the number of food items included in the analysis and the impact on climate change extrapolated with the energy intake. Each point represents one iteration of 5 %-points of observations included. After eight iterations, the estimated GHG emissions remained constant at 4.4 ± 2.3 kg CO_2-eq/capita/day (mean ± SD), regardless of the increasing number of food items included. The results of the analysis remained stable with the inclusion of 227 foods and beverages, representing 74 % of the energy intake, 84 % of the quantity consumed in mass and 77 % of the total protein intake. A comprehensive list of the food items included in the study, along with the food groups to which they belong, can be found in Appendix E, Table S5. The same methodology was employed to assess other environmental impact categories, including land use, water use, and fossil resource scarcity (Appendix D, Fig. S3). The extrapolated results remained stable after the inclusion of a similar number of food items as for climate change (227). It can thus be assumed that including this quantity of food items in this context is reliable for assessing the overall environmental impact of the Belgian diet.

The methodological framework described here provides a systematic approach to selecting food items for dietary environmental impact analysis. This enables precise estimation of the environmental footprint within the constraints of a limited food item selection. Such a systematic approach has not been found in the literature, where the assessment of the remaining food items of the diet and the selection of the number of foods to be included is often based on expert judgment or unclear. In certain instances, the remaining food and beverages were estimated using extrapolations based on primary data. These extrapolations were carried out using expert judgment and were based on similarities in types of food, production systems and ingredient composition (Sugimoto et al., 2020; Vellinga et al., 2019). Alternatively, some studies have opted to perform average analyses at the food group level. This is achieved by using the average intake by food group and average emissions by food groups (Murakami and Livingstone, 2018), while others have not provided sufficient detail on the selection process for the analysed food items (Masset et al., 2014; Vieux et al., 2020). It is acknowledged that the presented approach inherently introduces a degree of uncertainty compared to a comprehensive assessment covering all food items. However, the marginal gains in accuracy gained from such comprehensive assessments may not justify the additional computational and time burden.

4.2. Environmental impact of Belgian diets

4.2.1. The nutritional value and environmental impact of the Belgian diet

Table 1 presents a general overview of the nutritional aspects and environmental impacts attributed to the diet of the average Belgian (i.e. total population) children, adolescents and adults. The Belgian population consumes, on average, 2.6 kg of food and drinks per day, with 1.6 kg of these being beverages. This corresponds to an energy intake of 1903 kcal and an average protein intake of 74 g per day. On average 62 % of the protein consumed came from animal sources, 28 % from plant sources, and 10 % from mixed foods (containing both animal- and plant-based protein sources). Consumption and environmental impacts vary

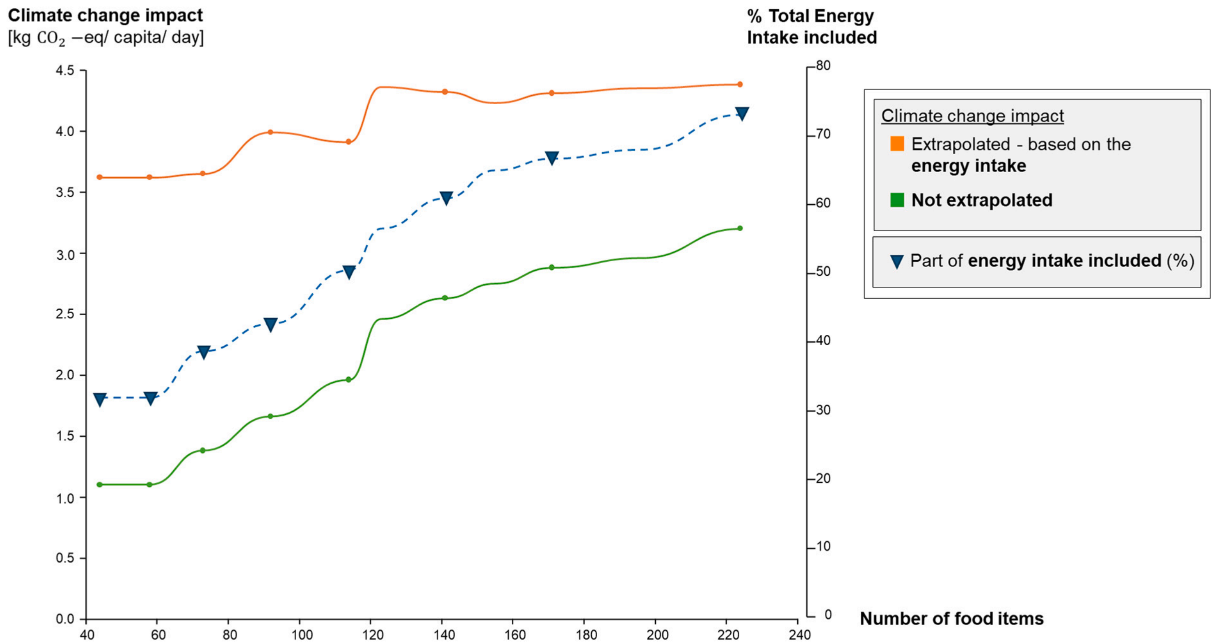

Fig. 3. Results of the iterative procedure for the impact on climate change of the average Belgian diet (kg CO_2-eq/capita/day).

Table 1
Nutritional and environmental aspects, for the total population, children aged 3–9 years, adolescents aged 10–17 years and adults' women and men aged 18–64 years. Results are expressed per capita and per day. Values are represented as mean and 95 % confidence interval (CI).

	Total population ($n = 3146$)		Children, 3–9 y ($n = 992$)		Adolescent, 10–17 y ($n = 928$)		Women, 18–64 y ($n = 637$)		Men, 18–64 y ($n = 589$)	
	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI
Nutritional aspects										
Quantity (kg)	2.6	(2.58–2.66)	1.77	(1.74–1.79)	2.14	(2.1–2.18)	2.60	(2.54–2.65)	3.08	(3–3.16)
Energy intake (kcal)	1903	(1873–1933)	1517	(1490–1543)	1883	(1845–1921)	1635	(1599–1670)	2312	(2250–2375)
Protein intake (g)	74.1	(72.9–75.3)	54.7	(53.6–55.9)	69.1	(67.5–70.7)	66.5	(64.9–68.1)	89.7	(87.2–92.2)
Animal-based protein (g)	46.4	(45.4–47.5)	33.4	(32.4–34.4)	42.1	(40.8–43.4)	41.9	(40.4–43.3)	56.8	(54.6–59.0)
Plant-based protein (g)	20.5	(20.0–20.9)	14.4	(13.9–14.8)	18.0	(17.5–18.5)	18.6	(18.1–19.2)	25.1	(24.2–26.1)
Mixed protein (g)	7.2	(6.9–7.5)	7.0	(6.6–7.3)	9.0	(8.5–9.5)	6.0	(5.6–6.4)	7.8	(7.1–8.4)
Environmental impact										
Climate change (kg CO_2-eq)	4.41	(4.27–4.54)	3.07	(2.97–3.16)	3.88	(3.75–4.01)	3.99	(3.83–4.16)	5.43	(5.14–5.72)
Water use (m^3)	0.14	(0.14–0.15)	0.10	(0.10–0.11)	0.12	(0.12–0.13)	0.14	(0.13–0.14)	0.16	(0.16–0.17)
Land use (m^2 crop-eq)	3.83	(3.71–3.95)	2.71	(2.62–2.80)	3.49	(3.37–3.62)	3.43	(3.27–3.59)	4.72	(4.46–4.97)
Fossil resource scarcity (kg oil-eq)	0.69	(0.68–0.71)	0.45	(0.44–0.47)	0.57	(0.55–0.58)	0.65	(0.63–0.67)	0.86	(0.82–0.89)

by age and gender. Children and adolescents have a lower environmental impact than adults. This is largely due to the lower amount of food consumed and the associated energy intake. It should be noted that adolescents tend to have a similar environmental impact as adult women. They have a lower intake in terms of quantity but a higher energy intake.

Downscaling the food system GHG emissions limit set by the EAT Lancet report (Willett et al., 2019) using the equal per capita principle (Ryberg et al., 2020), and the actual number of people on earth (7.88 billion), individual GHG emissions should not exceed 1.74 kg CO_2-eq per day. The present study found that an average Belgian emits 4.41 kg CO_2-eq per day, which is more than twice the limit. Furthermore, edible food waste at consumer level has not been accounted for. Insights from the Food Consumption Survey showed an under-reporting rate of 24 % (Bel et al., 2019), suggesting that consumption and environmental impact should be even higher.

4.2.2. *Impact per food group*

Fig. 4 illustrates the relative contribution of the different food groups to both nutritional and environmental aspects of an average Belgian diet. The main sources of energy intake are cereals, tubers, snacks, and dairy products, which together account for 61 % of the total daily average energy intake. Protein intake is mainly derived from red meat, cereals and tubers, dairy and eggs, poultry, and fish, which account for 84 % of the total protein intake.

The most significant contributors to climate change are red meat, beverages, dairy and eggs, and snacks. Animal products account for 56 % of Belgian's food and drink related GHG emissions. When considering only food, this rises to 67 % of total climate change impact. Beverages also have a significant impact on climate change (16 %). This includes alcoholic beverages (23 % of total GHG emissions from beverages), with beer being the largest contributor. Non-alcoholic beverages also have a notable impact (77 %), with coffee, water (mainly due to bottled water consumption), soft drinks, and juice consumption being the main contributors. The impact of bottled water consumption alone accounts for 99 % of the total climate change impact of water consumption. This is mainly due to the production of plastic bottles, as well as their distribution to retailers and households. It suggests that a shift from bottled to tap water consumption in Belgium could significantly reduce GHG emissions associated with water consumption, as also indicated by

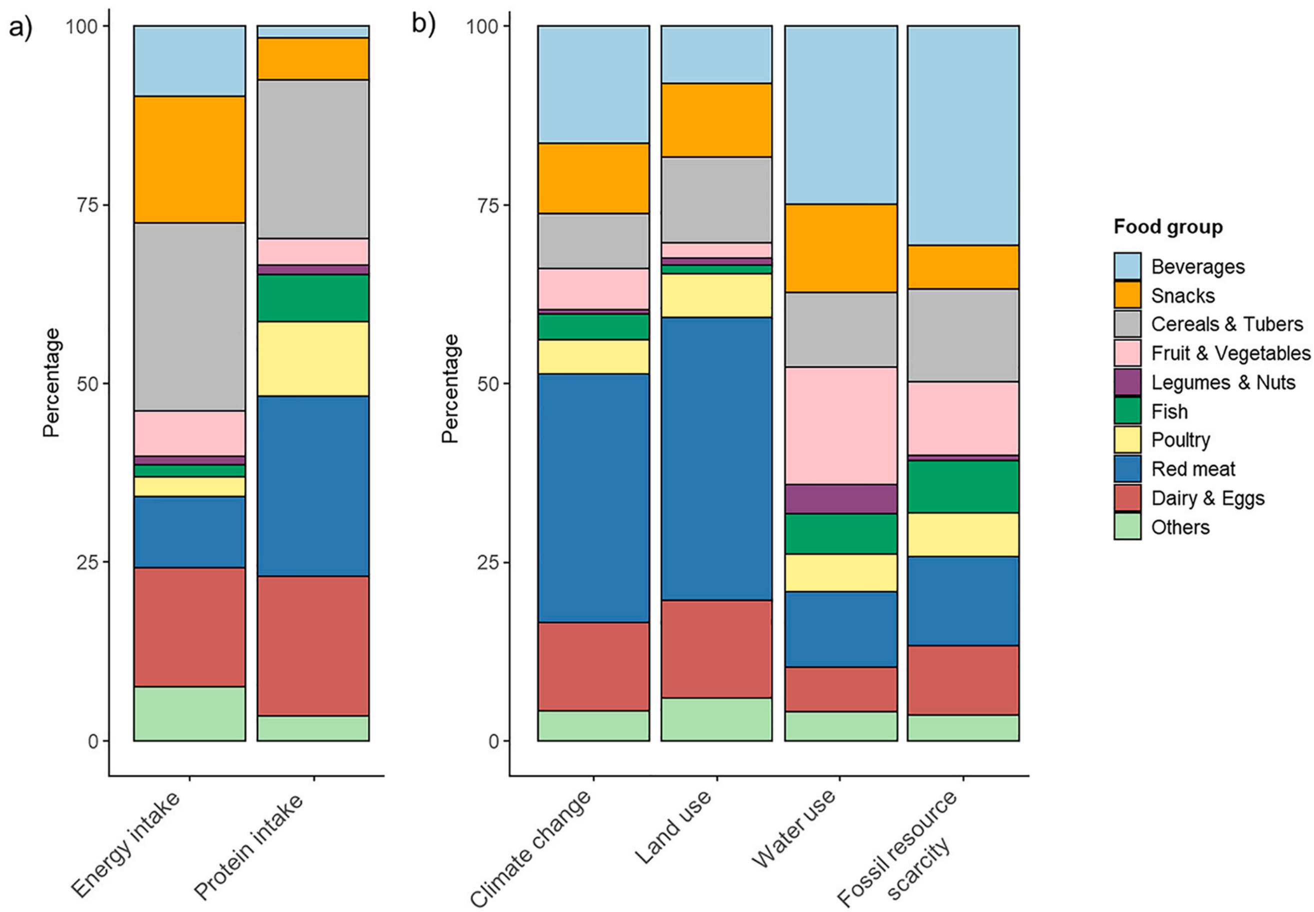

Fig. 4. Relative food groups' contribution to daily (a) energy and protein intake and (b) environmental impacts of the Belgian diet.

Thomassen et al. (2021).

Regarding land use, the trend closely mirrors that of GHG emissions, with beverages having a lower impact. The relative contribution of cereals and tubers, red meat and poultry is, however, slightly higher.

In terms of water use, beverages, particularly non-alcoholic ones, are the primary contributors, accounting for 24 % of the total, followed by fruit and vegetables contributing at 16 %, snacks at 12 %, and red meat at 10 %. Animal-based foods, in general, have a lower impact on water use, accounting for only 28 % of the total. Within the beverage category, coffee, juices, and soft drinks were identified as significant contributors to water usage. The impact of coffee is primarily associated with the cultivation of the beans and the subsequent processing until obtaining roasted coffee. The most significant impact of juices is observed at the fruit production stage. Fruits and vegetables are indeed known to have a high impact on water use (Meier and Christen, 2013). Among snacks, chocolate spread and chocolate biscuits were identified as the products with the greatest water use, with the cultivation of raw products (cocoa beans, milk and nuts) representing the most impactful step.

For fossil resource scarcity, beverages have the greatest impact (31 %), followed by cereals and tubers (13 %), red meat (12 %), and fruits and vegetables (10 %). The impact of beverages is primarily due to the production of plastic bottles. In the case of cereals, the production, packaging, cooking, and transportation stages exhibited similar levels of energy consumption. The impact is mainly due to the high quantity of cereals and tubers consumed, rather than because they are a high-impact food.

The small contribution of animal products to the water footprint was not observed in other studies (Harris et al., 2020; Mekonnen and Hoekstra, 2011), which found that the production of meat is more water-demanding than crop production. A crucial element in the present analysis is the application of the ReCiPe method, which assesses both the water demand and scarcity in the region under consideration (Huijbregts et al., 2017). In this study, it is assumed that all meat production occurs in Belgium, which is modelled based on French environmental parameters. Consequently, as water availability is evaluated to be good in France, the impact of animal products on the water footprint is smaller. However, it should be noted that the level of water availability in Belgium is lower than in France (Thyssen, 1998). Therefore, the water footprint of animal-based products is probably underestimated. Crops were produced in several countries, with greater water scarcity and less efficiency. This may explain the higher impact of plant-based products in that analysis. A comparable pattern was also identified in the Netherlands, employing the same method (Vellinga et al., 2019).

4.2.3. *Influence of protein sources*

The results of the food consumption survey indicate an animal-to-plant protein ratio of 2.2 (approximately 70/30). This ratio is based on the quantity of each type of protein consumed. Only animal and vegetable proteins have been utilized in the calculation of the ratio, mixed proteins being of unknown proportion. In terms of mass, red meat was the most important animal protein source, accounting for 25 % of the total protein intake. This was followed by dairy products and eggs, which collectively contributed 20 %, and poultry and fish, which contributed 10 and 6 %, respectively. With regards to plant protein sources, cereals and tubers were primary contributors, accounting for 22 %, followed by fruit and vegetables at 4 % (Fig. 4a). Surprisingly, pulses, nuts and meat substitutes collectively accounted for only 1 % of total protein intake. Despite pulses and nuts being known for their high protein content per 100 g of food (Singh, 2017), their relatively low consumption resulted in a low contribution to total protein intake.

The environmental impact and some nutritional aspects of diets across different quintiles of the population, characterised by the ratio of animal-to-plant protein intake, were assessed for the adult population. The results indicated no significant differences in energy intake (Fig. 5a), consumed quantity or age among the quintiles. However, there was a linear relationship between increasing quintile and total protein intake. This suggests that individuals who consume a higher proportion of animal protein also consume more protein overall while maintaining an equivalent energy intake and quantity consumed. This observation aligns with findings concerning plant-based diets, which typically have higher levels of plant protein but lower overall and animal protein intake (Halkjær et al., 2009; Mariotti and Gardner, 2019). The mean daily protein intake among Belgian women and men is 66 g and 89 g, respectively (Table 1). This exceeds the recommended daily intake of 52 g for women and 62 g for men on an omnivorous diet (Superior Health Council, 2019). Consequently, the transition to a greater proportion of plant proteins, even if it results in a reduction in the total protein intake, should not present a challenge in terms of meeting quantitative protein requirements. This is supported by the observation that individuals in the lower quintile exhibit an average protein intake of 66 g per day, irrespective of gender. It should be noted that these recommendations are intended for adults and that in certain circumstances, higher intakes may be necessary (e.g., during growth, pregnancy, etc.).

With regards to environmental impacts (Fig. 5b), climate change varied significantly across the quintiles. Diets with a higher proportion of plant-based protein were associated with lower GHG emissions. A similar significant linear trend was also observed for the impact categories of land use and, to a lesser extent, fossil resource scarcity. This outcome aligns with the known environmental impact, such as climate change and land use, of animal products, as illustrated in Section 4.2.2. No significant difference was found among the quintiles in terms of water use. This is consistent with the lower contribution of animal products to water use, as depicted in Section 4.2.2. The analyses were then adjusted for gender, region and energy intake, and no changes were observed in the relationships between the quintile and the diverse environmental impacts.

This study demonstrated an animal-to-plant protein ratio of 85/15 in the highest quintile (Q5), a ratio of 70/30 in the third quintile (Q3) and a protein ratio of 50/50 in the lowest quintile (Q1). A comparison between Q5 and Q1 revealed a significant reduction in GHG emissions and land use of 33 % and a reduction in fossil resource scarcity of 18 %. However, there was a small, non-significant increase of 8 % in water use.

The Flemish Green Deal protein shift (Omgeving Vlaanderen, 2021), initiated in 2021, aims to rebalance the consumption of animal and plant protein, transitioning from the current ratio to a more sustainable one of 40/60 *w*/w (equivalent to 0.66) by 2030. To estimate the environmental impact of such a shift, individuals from the consumption survey were sorted based on their protein ratios. Those who consumed the least animal protein were selected first, with individuals from the lower ratios

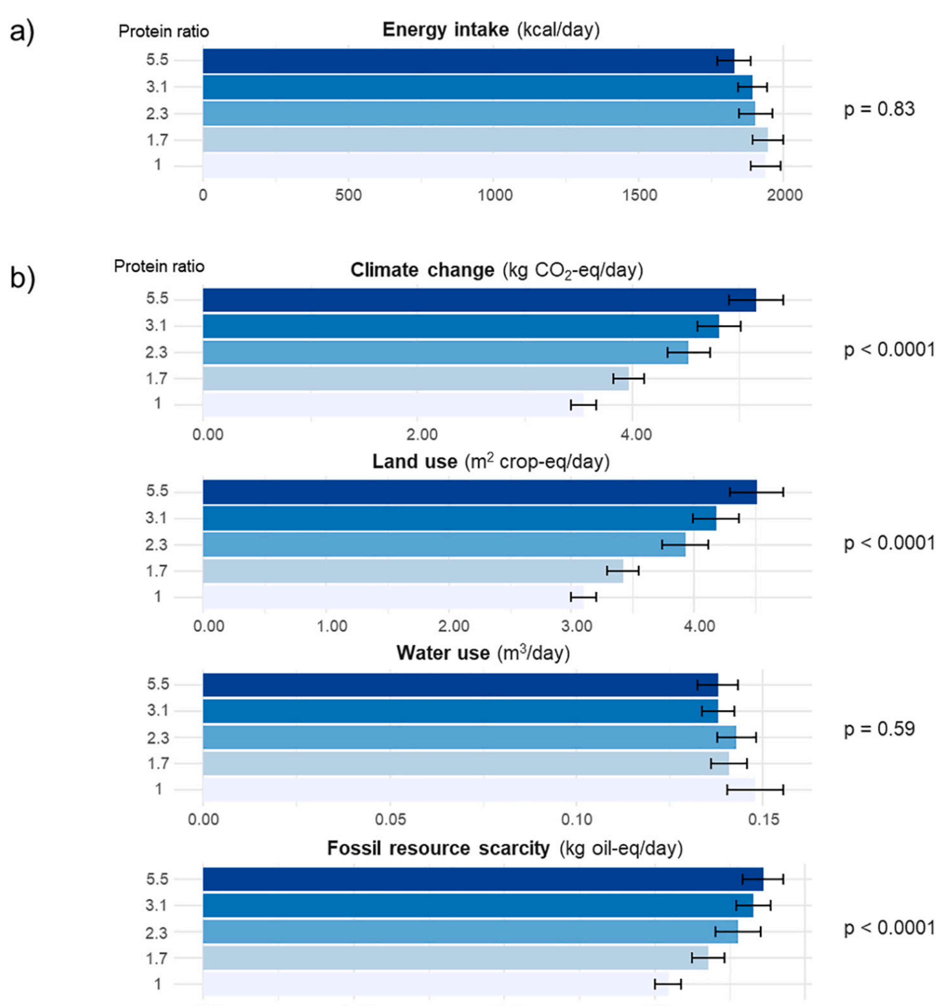

Fig. 5. (a) Daily energy intake and (b) environmental indicators according to quintile of protein ratio for adult Belgian population ($n = 1226$). Error bars represent the Standard Error of the Mean. $p < 0.05$ was considered statistically significant for linear relationship.

being included up to a ratio of 0.66. Subsequently, the number of individuals included in the sample was increased gradually until the target average ratio of 40/60, was reached. The resulting sample of 94 adult participants was considered representative. Transitioning from the third quintile, which includes the median, to the 40/60 ratio resulted in significant reductions in GHG emissions (29 %), land use (26 %) and fossil resource scarcity (22 %), accompanied by a non-significant increase in water use (10 %). It should be noted that the mean protein intake of the group was 63 g per day (for both women and men), which remains above the recommended levels set forth by the Superior Health Council. Fouillet et al. (2023) have indicated that a shift from the current ratio in France (67/33) to the recommended ratio of 30/70 would result in a 50 % reduction in climate change impact and a 40 % and 20 % reduction in land use and fossil resource use, respectively. However, an increase in water use of between 25 and 50 % was estimated as a result of the shift (Fouillet et al., 2023). The study differs from the present case in that it models diets and does not represent "real" diets, whereas the present case does. Moreover, the LCA method used is not the same. Nevertheless, the overall picture is similar.

In this study, such a shift towards greater vegetable protein consumption resulted in GHG emissions of 3.46 kg CO_2-eq/day per adult. This represents a significant reduction in comparison to the actual average adult emissions of 4.8 kg CO_2-eq/day. However, this amount remains above the targeted threshold for maintaining a 'safe operating space' for climate change, as outlined by Willet et al. in the EAT Lancet report (Willett et al., 2019). Regarding the observed 10 % non-significant increase in water footprint under the 40/60 scenario, it is plausible that the actual figure for Belgium might be even lower. This consideration arises from the potential underestimation of the water footprint for animal products, as discussed in Section 4.2.2.

4.2.4. Influence of processing levels on environmental impact

The Food Consumption Survey revealed that, on average, 36 % of the food and beverages consumed in Belgium are considered ultra-processed, accounting for 50 % of the total energy intake (Fig. 6a). Gender was found to have no noticeable correlation with UPF consumption. However, age groups considerably influenced the results, with children and adolescents consuming a notably higher proportion of UPF (61 %) compared to adults (46 %).

Fig. 6b illustrates that in Belgium, UPF are responsible for a considerable proportion of the total environmental impact of the Belgian diet. In particular, they contribute to 50 % of the climate change impact, 51 % of the land use impact, 41 % of the water use impact, and 38 % of the fossil resource scarcity. The largest contributors to GHG emissions and land use are ultra-processed meat, snacks, and dairy. In terms of water usage, snacks are the largest contributor, followed by non-alcoholic beverages and ultra-processed meat. For fossil resource consumption, non-alcoholic beverages, ultra-processed meat and dairy have the greatest impact. It is worth noting that alcoholic beverages, while not classified as ultra-processed in this study, also have a significant impact on fossil resource scarcity. The second largest contributor to environmental impact is the NOVA 1 category, which accounts for 34 % of GHG emissions, 31 % of land use, 45 % of water use and 42 % of fossil resource scarcity. The primary source of GHG emissions in NOVA 1 is red meat, followed by non-alcoholic beverages and fruits and vegetables. In terms of land use, red meat is the most significant contributor, followed by non-alcoholic beverages, and poultry. Non-alcoholic beverages are the most significant contributor to water use, followed by fruits and vegetables, and then poultry. In terms of fossil resource scarcity, non-alcoholic beverages are the largest contributor, followed by fruits and vegetables, and then fish. Processed foods (NOVA 3) and culinary processed ingredients (NOVA 2) were found to have a lower contribution to the four evaluated environmental impacts. Relative contribution of food groups per NOVA classification can be found in Appendix E, Table S6.

Few countries have investigated the environmental impact of UPF consumption using national samples. In Brazil, UPF were estimated to account for 12 % of total GHG emissions and 15 % of the water footprint

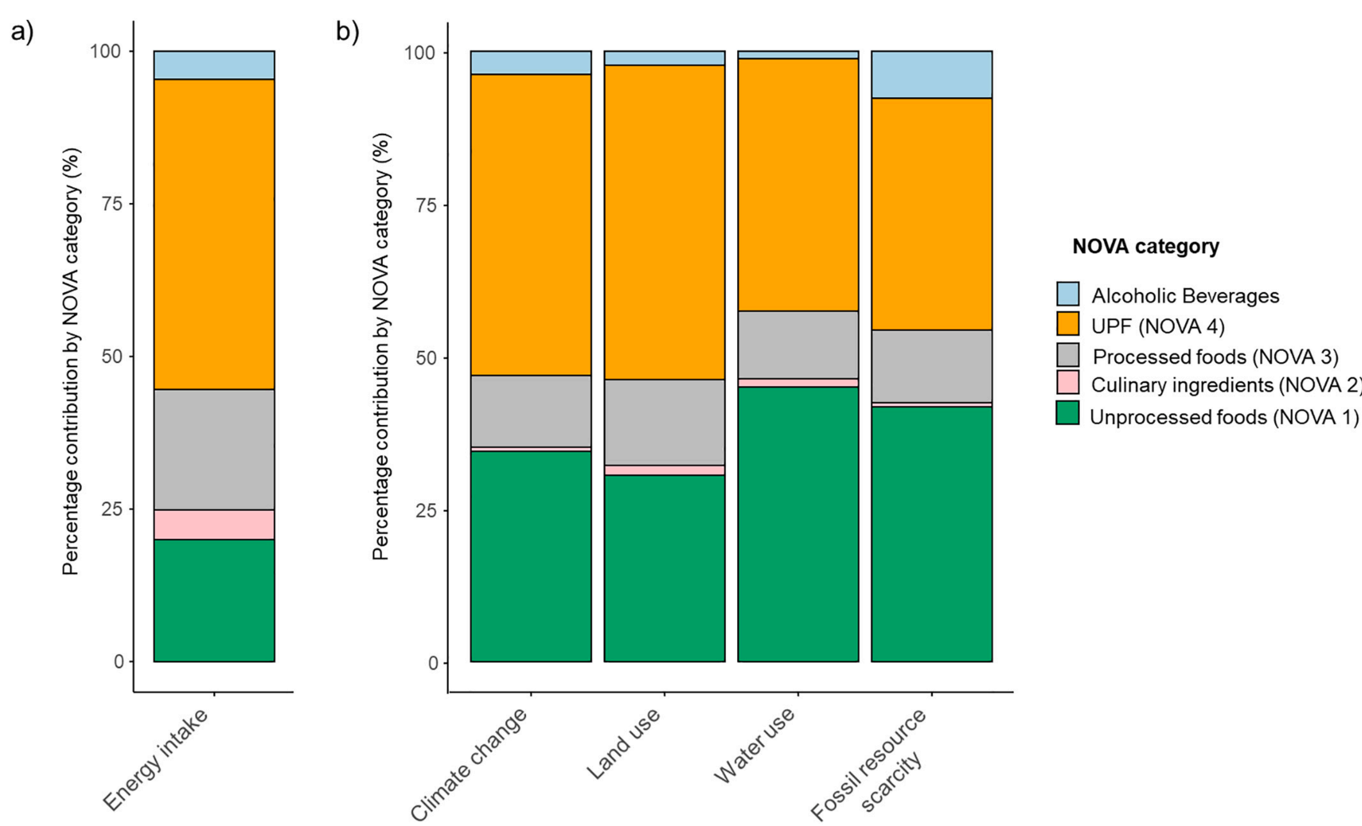

Fig. 6. Relative contribution of level of processing to (a) daily energy intake and (b) environmental impacts of the Belgian diet.

(Garzillo et al., 2022). In France, 24 % of GHG emissions, 23 % of water use, 23 % of land use and 26 % of energy demand were associated with UPF consumption (Kesse-Guyot et al., 2023). Conversely, in the Netherlands, results more closely aligned with those of Belgium, where UPF consumption was associated with 45 % of total GHG emissions and 23 % of blue water use (Vellinga et al., 2022). These variations in UPF related environmental impact across countries can be attributed to differences in the proportion of energy intake or quantity derived from UPFs. In Brazil, UPFs accounted for 20 % of energy intake, in France, they accounted for 20 % in weight, while in the Netherlands, they accounted for 61 % of energy intake. Furthermore, direct comparisons are challenging due to disparities in dietary habits, data collection methods, LCA methodologies and the NOVA classification system.

UPF contributed significantly to the environmental impact and accounted for a significant proportion of energy intake. However, the extent to which UPF consumption resulted in a higher environmental impact compared to less processed foods remained uncertain. To address this gap, a quintile analysis was conducted based on the percentage of energy intake from UPF. The study revealed a notable positive correlation between the increasing proportion of energy intake from UPF and age ($p < 0.0001$) (Appendix E, Table S7). Children and adolescents tend to consume smaller quantities of food and consequently exhibit a reduced environmental impact, as illustrated in Table 1. To avoid bias from age groups, a specific analysis of UPF quintile focusing on adults was performed and the results are illustrated in Fig. 7. The higher the percentage of energy intake from UPF, the greater the daily calorie consumption (Fig. 7a). This trend was also observed in other studies (Garzillo et al., 2022; Hall et al., 2019; Kesse-Guyot et al., 2023; Martini et al., 2021) reinforcing the association between UPF consumption and heightened energy intake. Conversely, the present study found a negative linear association between UPF quintiles and total daily food consumption in grams, indicating a decrease in overall food intake as UPF consumption increased ($p = 0.0023$). The age trend across all quintiles remained linear within the adult sample, with decreasing differences ($p < 0.0001$), indicating that younger individuals are consuming a greater proportion of UPF. No linear relationship was identified concerning protein intake.

With regards to environmental impacts (Fig. 7b), a linear relationship was observed between increasing UPF quintile and increasing GHG emissions and land use impacts. No significant relationship was found between UPF quintile and water and fossil resource scarcity. These results remained consistent after adjustment for gender and region.

In France, comparative analyses of UPF quintiles revealed consistent trends with our study, showing increased energy intake, GHG emissions, and land use impacts with increasing UPF consumption (Kesse-Guyot et al., 2023). Furthermore, the authors reported an increase in the use of fossil resources and a decrease in water usage, which contrasts with our findings that show no clear linear trend. In Brazil, however, no significant trend was identified for GHG emissions (Garzillo et al., 2022). Conversely, a linear trend was observed for water use, which suggests the potential for regional variations in environmental impacts associated with UPF consumption (Garzillo et al., 2022). These variations highlight

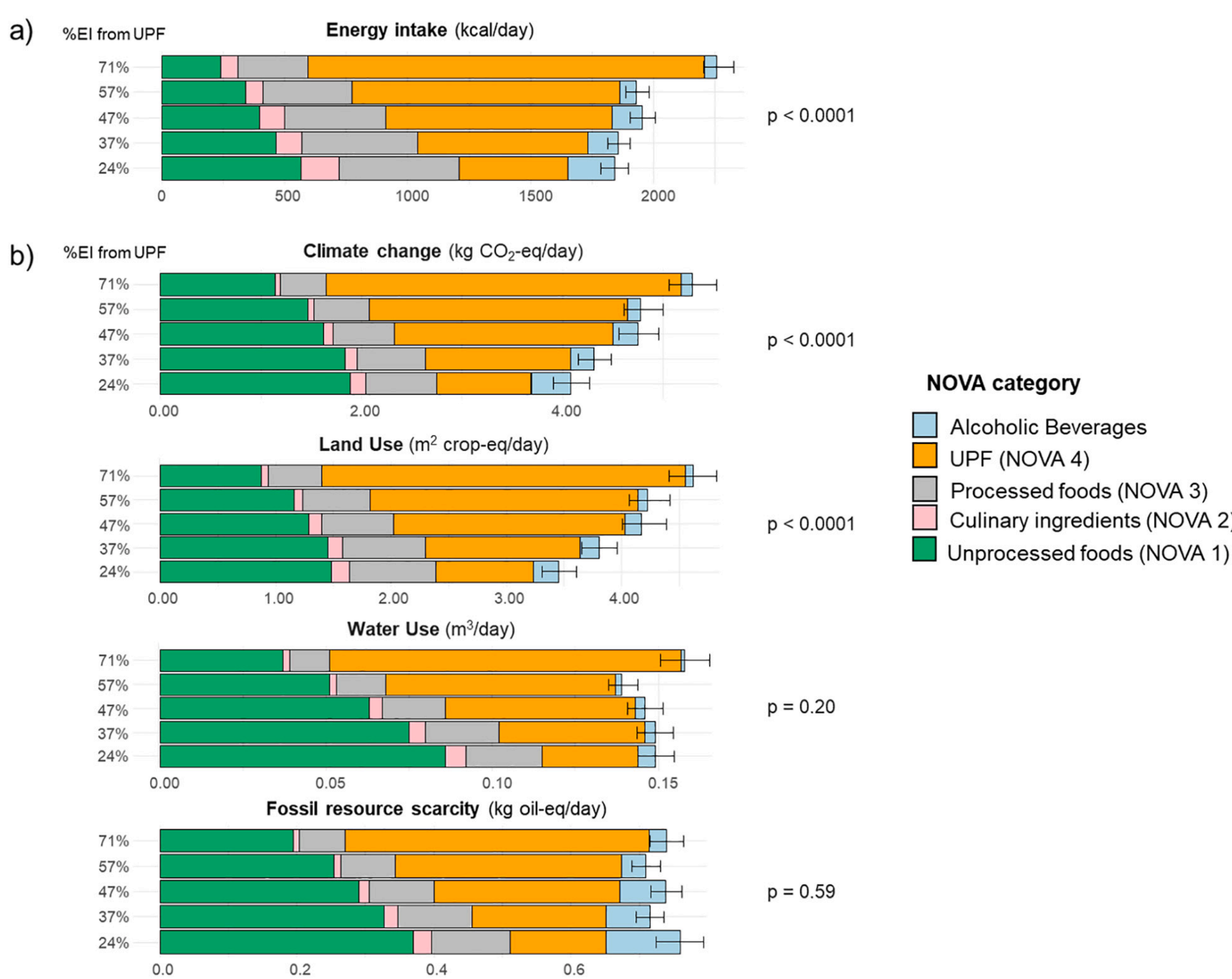

Fig. 7. (a) Daily energy intake and (b) environmental indicators according to UPF quintiles for adult Belgian population ($n = 1226$). Error bars represent the Standard Error of the Mean. $p < 0.05$ was considered statistically significant for linear relationship.

the intricate interplay between dietary patterns, environmental impacts, and regional factors, emphasising the need for further investigation into the nuanced relationships between UPF consumption and environmental sustainability across different geographical contexts.

In order to determine whether the observed increase in certain environmental impact across quintiles is linked to the increase in energy intake, the analysis was adjusted for energy intake. This adjustment entailed incorporating energy intake as a covariate in the model. By doing so, the potential influence of energy intake on the dependent variable was statistically controlled for. This resulted in significant differences in the results before and after the adjustment. The linear trend for climate change dissipated after the adjustment ($p = 0.087$), but the trend for land use remained significant ($p = 0.013$). The relationship between water use and UPF quintile was not statistically significant. Conversely, a negative linear correlation was observed between fossil resource scarcity and UPF quintile ($p = 0.0002$). This negative relationship can be explained by the higher energy intake from alcoholic beverages in the lower quintile compared to the higher quintiles. Alcoholic beverages were found to have a greater impact on fossil resource scarcity (Fig. 6). In Brazil, when the analyses were adjusted for energy intake, the linear relationship for water use disappeared and it was still not significant for GHG emissions (Garzillo et al., 2022). In France, after adjustment for energy intake, water use was even more negatively associated with increased UPF consumption, climate change was not associated anymore, and energy demand was also negatively associated (Kesse-Guyot et al., 2023). These results are consistent with those previously reported, indicating that the impact decreases across quintiles.

Similar conclusions were drawn from the analysis of the group of children and adolescents ($n = 1920$) (data not shown), except for land use, where the linear relationship was no longer significant after adjustment for energy intake. There was also no significant difference in age between quintiles.

4.3. General discussion

4.3.1. Key insights and interpretation

This study highlights the importance of considering a range of environmental impact categories beyond solely climate change. The analysis reveals that red meat, beverages, and snacks consumption contribute significantly to environmental burdens. Notably, in Belgium, the consumption of red meat exceeds the recommended level from the Superior Health Council (Superior Health Council, 2019) by more than double. Snacks and some beverages are considered discretionary foods, which are not nutritionally necessary and can be harmful to health (Coxon et al., 2020).

Transitioning towards diets with a higher proportion of plant-based protein represents a positive step towards reducing some environmental impact indicators of the Belgian food system. However, our findings underline the need for complementary changes in other consumption patterns, multiple practice change (depending on the context, organic production, agroecology, integrated or conservative agriculture are possibilities (Poore and Nemecek, 2018)) and the food supply chain (promoting local sourcing and seasonal alignment) in order to fully meet sustainability targets. Moreover, it is important to consider the issue of water usage, which is likely to become a more pressing concern in the future.

UPF are widely recognized for their negative health impacts, especially their association with non-communicable diseases (Lane et al., 2024; Moradi et al., 2021; Shu et al., 2023; Suksatan et al., 2022). However, UPF tends to generate less household food waste compared to other NOVA categories. Indeed, a recent study indicates that the proportion of total household food waste related to unprocessed and minimally processed foods (NOVA 1) is 87 %, against 11 % for UPF (Barker et al., 2023). This is primarily attributable to the additives and typical packaging of UPF that permit a longer shelf life than that of fresh products (Monteiro et al., 2019). Nevertheless, present study indicates that UPF consumption, particularly of ultra-processed meat, snacks, dairy, and ultra-processed drinks, is associated with higher energy intake, resulting in increased GHG emissions and land use.

The findings of this study indicate that a reduction in the consumption of high-impact and unnecessary foods represents a crucial initial step in reducing environmental impacts. Furthermore, the incorporation of the concept of UPF into dietary policy appears to be a crucial step, given the considerable environmental impact and prevalence of consumption among the Belgian population. A well-balanced diet is of great importance for human health. It is widely acknowledged that dietary risks are major contributors to the global burden of disease (GBD 2019 Risk Factors Collaborators, 2020). Future research should investigate health impact to provide a comprehensive assessment of Belgian food consumption and its impact on both public health and environmental sustainability. Dietary recommendations must consider both environmental and health outcomes to offer a holistic solution to the pressing challenges of modern food systems.

4.3.2. Uncertainty integration

Several sources of uncertainty have been identified in this study that could affect the results and their comparison with other studies. Uncertainty in the data arises from the food consumption survey. There is a documented underreporting of energy intake, particularly notable among women (Bel et al., 2019), implying potential underestimation of certain food intakes and associated environmental impacts. To account for the uncertainty around the mean, 95 % confidence intervals were used to provide a clearer picture of the potential range to be considered. Certain gaps in the LCI dataset, as highlighted above, add further uncertainty. In addition, the use of a French database to represent Belgian food production introduces methodological uncertainty, as differences in agricultural practices, land use and resource availability between the two countries may not be fully captured. While a more accurate approach would require a Belgian-specific dataset, such data are currently not available. Furthermore, the model itself, like any simplified system, is subject to uncertainty due to assumptions made during its construction. To account for this, the assumptions and simplifications are described in detail in the Methods section. Different LCA methodologies may use different impact categories and characterisation factors, adding another layer of uncertainty. However, two LCA's are not comparable if they do not use the same methods and databases, this inherent uncertainty is a key challenge in LCAs (Institute for Environment and Sustainability (JRC), 2010).

4.3.3. Opportunities and critical reflection

Firstly, an iterative methodology was used to determine the optimal number of food items to include in our analysis. This approach ensures that our environmental impact estimates are as accurate as possible and could provide an approach for future research in this area. Secondly, the LCA boundaries extend from farm to fork, covering all stages of the food supply chain, including end-of-life packaging considerations. In addition, this study evaluated multiple environmental impacts, including not only climate change, but also other environmental indicators such as water use, land use, and fossil resource scarcity. Furthermore, the use of the Belgian National Food Consumption Survey data is an important strength, as it includes a substantial number of 3146 participants and provides a representative sample of the Belgian population. This ensures the robustness and generalisability of our findings to the wider population. Finally, the supply chain was adapted for Belgian consumption, using accurate trade data, which allowed to model the environmental impact of food items more accurately. Taken together, these strengths enabled us to conduct a comprehensive environmental assessment of the Belgian diet, providing a holistic view of the environmental footprint associated with food consumption in Belgium.

Areas for future research include enhancing the accuracy of data in this study. Firstly, incorporating consumer-level edible food waste data is crucial to fully understanding the true environmental impact of the

Belgian diet. Previous studies have estimated that on average in the EU, the consumption phase was responsible for 46 % of total food waste. This includes edible and non-edible waste. However, analysis highlights that edible sources constitute the majority of food waste across various food groups (Caldeira et al., 2019). Secondly, although Agribalyse is accurate and very detailed, there are some limitations to its use. It did not consider business-to-business packaging, nor transport between the retailer and the household. In terms of processing, the focus was on operations that affect yield or mass, and less attention was paid to mechanical operations (e.g., slicing, pressing) (Asselin-Balençon et al., 2022), which may have implications for the environmental impact assessment of UPF. Furthermore, the utilisation of a French LCI database may influence the outcomes of water usage, given that water scarcity is less prevalent in France. To address this, analyses to adapt the water requirement ratio for Belgium were conducted, specifically for meat and dairy products, which were considered 100 % Belgian. This adjustment resulted in a 3 % increase in the total water footprint, which did not alter the conclusions drawn. Moreover, the study could not take into account the farming system for the environmental impact assessment, using average French data for food production. This may lead to potential inaccuracies in the environmental impact assessment. Finally, it should be noted that the consumption data used was collected in 2014–2015. Given the rapid evolution of consumption patterns, it would be beneficial to update this research with more recent data (once Belgian food consumption data for 2022–2023 becomes available) to account for potential shifts in consumption and provide a more accurate reflection of current patterns.

This study provides insight into the relationship between UPF consumption and environmental impact. However, there are some remaining challenges. Firstly, the environmental impact assessment did not include certain ingredients commonly found in UPFs, such as artificial sweeteners, flavourings, stabilisers and texture modifiers. The lack of quantification for these ingredients implies that the environmental impact could be underestimated. Secondly, UPF are known to use extensive packaging (Monteiro et al., 2019), which is a major source of environmental waste with global disposal implications. However, this specific impact of UPF packaging could not be captured in this study. Consequently, the impact of packaging may be underestimated. These considerations underscore the importance of interpreting current findings with caution. Future research should aim to address these gaps to provide a more comprehensive understanding of the environmental implications of UPF consumption.

5. Conclusions

This study employs a novel iterative methodology to systematically identify the food items included in the analysis. This approach enabled the comprehensive analysis of the environmental impact associated with the Belgian diet, revealing significant findings. Certain food groups were identified as having a significant impact on the environment across different environmental impacts, including red meat, snacks and beverages. Furthermore, the current high ratio of animal-to-plant protein consumption serves to illustrate the substantial environmental burden associated with such dietary habits. While a shift towards a 40/60 ratio (as recommended in the Green Deal protein shift) is a promising approach for reducing climate change, land use and fossil resource scarcity, additional measures are necessary to ensure that we stay within the planetary boundaries. Moreover, the consumption of UPF has been identified as a significant contributor to the diet, leading to increased energy intake in high consumers, which subsequently leads to elevated climate change and land use impacts.

Integrating health considerations alongside the environmental impact of the diet is crucial before making any recommendation, as dietary recommendations for sustainable diets must balance environmental sustainability with human well-being. Further research aims to elucidate the link between dietary risk factors and health outcomes in the Belgian context, identifying trade-offs and synergies between environmental and health impacts.

CRediT authorship contribution statement

Claire Dénos: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Stefanie Vandevijvere:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition. **Lieselot Boone:** Writing – review & editing, Validation, Supervision. **Margot Cooreman-Algoed:** Writing – review & editing, Validation, Supervision. **Michiel De Bauw:** Writing – review & editing, Validation. **Wouter M.J. Achten:** Writing – review & editing, Validation, Supervision, Funding acquisition. **Jo Dewulf:** Writing – review & editing, Validation, Supervision, Funding acquisition.

Funding

This work was supported by Belspo [B2/223/P3/SUSFOODBEL] and is part of the SUSFOODBEL project.

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.

Acknowledgements

The authors want to thank the Ministry of Health for providing funding for the national food consumption surveys of 2014/2015.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.10.008.

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