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Regional food consumption in Italy, a life cycle analysis

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A R T I C L E I N F O

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A B S T R A C T

Urbanization and globalization have led to an increasing concern and focus on the sustainability of the food sector, particularly in discussing the composition of consumers' diets. This study examines Italian consumption habits, categorizing them into four macro-geographical areas (North-West, North-East, Center, South, and Islands), utilizing public data obtained from surveys including 3323 individuals, and assesses their environmental impacts through the application of the Life Cycle Assessment methodology. The findings unveil distinct dietary patterns across Italian macro-regions, indicative of cultural disparities, and present avenues for promoting environmentally sustainable dietary choices. The study identifies meat consumption as the primary environmental concern across all macro-regions, with fish emerging as a secondary contributor to particulate matter formation. Pork and poultry exhibit notable impacts within toxicity-related categories. Additionally, the research underscores challenges in data collection, notably the absence of a site-specific Italian database, and underscores the necessity for more recent consumption data to accurately capture contemporary Italian dietary habits. Finally, the study demonstrates that addressing the issue from a macro-regional perspective allows for more targeted and dedicated cultural interventions.

List of abbreviations

Freshwater Ecotoxicity Potential	FETP
Functional Unit	FU
Green House Gases	GHG
Global Warming Potential	GWP
Italian LCI Database of Agri-Food Products	ILCIDAF
Istituto nazionale di ricerca per gli alimenti e la nutrizione	INRAN
Life Cycle Assessement	LCA
Life Cycle Inventory	LCI
Life Cycle Impact Assessment	LCIA
Land Use Potential	LOP
North-East	NORTH-E
North-West	NORTH-W
Particulate Matter	PM
Particulate Matter Formation Potential	PMFP
South and Islands	SOUTH-I
Studio consumi alimentari italiani	SCAI
Water Consumption Potential	WCP

1. Introduction

The environmental implications related to the surge in food production and consumption drove an urgent need for a decisive shift towards more sustainable supply chains and diets (Willett et al., 2019). Current food systems are considered responsible for several environmental implications, among which biodiversity loss (Lambin and Meyfroidt, 2011; Turner et al., 2007), eutrophication (Gephart et al., 2016) and deforestation (Garnett et al., 2014; Kissinger et al., 2012) and especially climate change, contributing to 34% of global greenhouse gas (GHG) emissions (Crippa et al., 2018). The increasing world population, predicted to reach around 9.7 billion people by 2050 and 11.2 billion by the end of 2100 (United Nations Department of Economic and Social Affairs, 2022), aggravates the potential issues, projecting the food demand to grow by +70% (King et al., 2017) and hindering the achievement of food security targeted by the 2030 Agenda for Sustainable Development (Mc Carthy et al., 2018). The food sector is unavoidably linked to agriculture, which both contributes to and is affected by climate change. In fact, on the one hand, agriculture is responsible for the release of 24% of GHG into the atmosphere, while on the other hand, extreme weather events affect crop yields and food prices (Vogel et al., 2019). The issue is also stressed by the one-third of all food produced for human consumption that is lost or wasted throughout the supply chain, from initial agricultural production down to final phases associated with

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food consumption (i.e., preservation, cooking and processes related to waste disposal) (FAO, 2011; Boccarossa et al., 2023), representing a loss of valuable products and resources (Wang et al., 2024). Combining the growing food demand with the consequent natural resource depletion and environmental degradation, the current food system does not have the prerequisites to be sustainable enough (Sala et al., 2017). In an era of increasing environmental concerns, understanding the environmental impact of consumption habits is pivotal to drive new ethical and sustainable choices, by also contributing to the mitigation of the environmental impacts. (Notarnicola et al., 2017; Hartmann et al., 2021).

According to Hartmann and Siegrist (2017), the lack of awareness of the negative impact that food production has on the environment results in non-sustainable food choices. Dietary preferences are often deep-rooted in cultural, religious, and traditional identities, which can make it challenging to alter long-standing eating behaviours (Cavaliere et al., 2023). The correction of dietary patterns, in addition to the reduction of food waste, represents one of the four key strategies to advance food sustainability (Garnett, 2013; Chang et al., 2022). Indeed, the reduction of high-impacting foods consumption (e.g., meat and derivates) and the embracement of vegetarian diets, based on local and seasonal products, may have significant benefits to the environment and the ecosystem (Himics et al., 2022; Sheppard and Bittman, 2015). The dietary transition towards more sustainable dietary patterns plays a pivotal role in the mitigation of environmental issues (Carvalho et al., 2023; Green et al., 2023), increasing the demand for foods that are both nutritious and less impacting (Mullen, 2020; Seed and Rocha, 2018). The knowledge of the environmental impact of a comprehensive dietary habit can serve as valuable information to guide consumer choices (BEUC, 2020), empowering consumers to take actions that not only benefit their health but also contribute to reducing the overall burdens of the food system (Cavaliere et al., 2023) but also to define policies aimed at promoting the dietary transition (Notarnicola et al., 2017).

The Italian agricultural sector mainly relies on the Mediterranean food chain and contributes to 8.6% of the national GHG emissions, making it the second-largest source of climate-related gases after energy production at the national level (UNFCCC, 2022). The Italian diet is renowned worldwide for its diversity, quality, and cultural significance, even if it was demonstrated that consumers' preferences have changed rapidly over the years and are nowadays very dynamic. In particular, some authors (Cavaliere et al., 2023; Veronese et al., 2020; Leone et al., 2017), recently stated that the current Italian diet does not completely reflect the original Mediterranean tradition, characterised by high consumption of vegetables, fresh fruit, legumes, and cereals (Trichopoulou et al., 2003; Bach-Faig et al., 2011), but it is becoming more similar to Western diets (eating habits prevalent in countries such as Europe, North America, and Oceania) with high consumption of animal-based foods, especially red meat (CIHEAM/FAO, 2015). Nonetheless, these considerations aim to categorize a very diverse diet which, despite showing some similarities to Mediterranean and Western diets, will ultimately vary for each individual case. For the case study, we believe this definition can help contextualize the work within a diet with Mediterranean roots, even though it may not fully reflect it in practice.

In pursuing sustainable dietary choices, the Life Cycle Assessment (LCA) methodology plays a pivotal role in uncovering the intricate environmental dimensions of food consumption. LCA is a systematic and scientific approach that provides a comprehensive evaluation of the environmental impact of a product or process throughout its whole life cycle (ISO, 2006a,b). In the context of food consumption, LCA can be applied to various aspects, such as individual food items (Zingale et al., 2022; Ferronato et al., 2021), specific food production methods (Silva and Sanjuán, 2019), meals (Volanti et al., 2022b; Arfelli et al., 2024a; 2024b; Cucurachi et al., 2019) or comprehensive dietary choices (Baroni et al., 2007; Donati et al., 2016; Piccinelli et al., 2023; Dixon et al., 2023). The use of LCA to assess the food sector and more generally its supply chain has been increasing over time: to date, around 2675 products (articles, reviews, and book chapters) were found in scopus.com which includes the keywords "food" and "LCA". However, many challenges arise due to the intrinsic variability of the food systems, such as agricultural practices and climatic conditions, making the assessments difficult to extend beyond the context of evaluation. Additionally, LCA studies highlight the importance of considering various environmental burdens beyond just climate change to evaluate alternative dietary scenarios (Meier and Christen, 2013; Poore and Nemecek, 2018; ISO, 2006a,b). In line with this, the proposed study aims to apply the LCA methodology to compare different Italian diets from an environmental point of view. The idea is to screen the citizens' alimentary behaviours, by offering valuable insights into the environmental footprint per geographical macro area and depict the contribution of each component to mitigate the overall burden. The proposed top-down approach enables the identification of the hotspot foods within the dietary habits of different groups of people (i.e., at the regional or national level) and to mitigate the associated impact by reducing their consumption at a regional and national level. This comprehension would allow decision-makers to incentivize the reduction of certain foods and to monitor the progress of the strategy.

2. Materials and methods

LCA is a scientific and operational tool employed to perform a comprehensive analysis of the whole life cycle of a system or product under investigation. This methodology is guided by international standards, specifically ISO 14040 and ISO 14044, which lay down fundamental concepts and criteria for running the methodology (ISO, 2006a, b). The LCA consists of four steps: Goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation.

2.1. Goal and scope definition

The main objective of this study is to estimate the potential environmental impacts of the Italian diet focusing on regional variations among the peninsula (North-West, North-East, Center, South and Islands, extended description in 2.2). The comparison of the regional habits is projected to i) allow the identification of sub-national hotspots and critical food items; ii) stimulate a discussion on how to reduce their consumption, such as by replacing them with less environmentally impactful options; iii) propose a top-down approach to adjust the food habits at the national level to reduce the comprehensive environmental impacts of diets; and iv) propose an innovative communication strategy aimed at optimising the communication and to increase the sensitiveness of consumer on the topic. In addition, the study sought to provide an approach applicable to different spatial and temporal contexts, adaptable to different data sets related to the food habits of more countries and regions. This preliminary assessment lays the groundwork for a deeper discussion to identify more sustainable dietary alternatives.

The system boundaries include all the upstream (raw material and semi-finished ingredients production, the extraction and generation of the energy carriers, and all the transportation involved up to the processing industry) and core activities (all the resources and energy consumption, and emissions related to the food industrial processing), following a from *cradle-to-gate* approach (Fig. 1). Packaging was excluded from the analysis due to its great variability, not always related to the food contained and sometimes affected by marketing reasons (Williams and Wikström, 2011; Arfelli et al., 2024a; 2024b). Moreover, the packaging average contribution to the environmental impacts shifts around 5–10% (Williams and Wikström, 2011). The cooking phase was also excluded due to the absence of data related to the type of equipment used in kitchens as well as material and energy balances associated to the cooking phase of each food product. Moreover, previous studies have indicated that the cooking phase closely depends on the technology of the equipment (e.g., electric or gas ovens), the cooking time, and also the discretion of the kitchen users (Hager and Morawicki, 2013; Pathare and Roskilly, 2016).

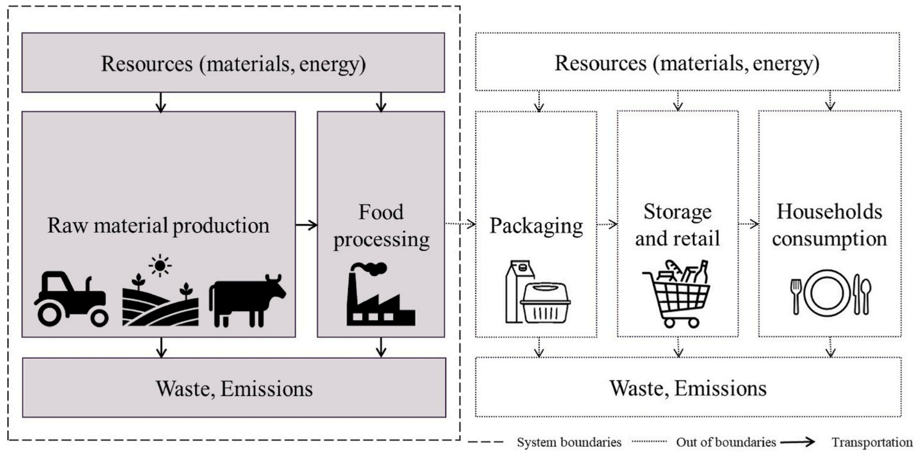

Fig. 1. System boundaries include the phases highlighted in grey, which include the production and processing stages. The phases in white boxes, instead, are those excluded from the study.

The downstream phases (e.g., distribution activities, retail sales, consumption, disposal of the packaging and food waste) were not included in the assessment since they were out of scope and they are predicted to provide a marginal influence on the environmental burdens (Ritchie and Roser, 2019; Henriksson et al., 2021).

The selection of the functional unit (FU), especially in the case of LCA applied to the food sector, generally depends on the objectives of the study (Cucurachi et al., 2019). Historically, early approaches adopted a mass-based unit (Clune et al., 2017; Mondello et al., 2018; Recanati et al., 2018), offering comparisons between equal amounts of different products. While this approach certainly provides valuable information in absolute terms, it entirely neglects the nutritional variable, which, on the other hand, should be considered in the assessment of different diets. To address this issue, more recent studies have attempted to include the nutritional variable in the assessment by developing complex indicators (Volanti et al., 2022b; Zingale et al., 2022) or indirectly incorporating it into the evaluation, choosing pre-established and balanced meals as FU (Arfelli et al., 2024a; 2024b). If the goal is to compare different foods to facilitate consumer choice of one food item over another, the choice of the FU undoubtedly represents a critical and influencing aspect. However, considering a broader perspective, we believe that examining the annual dietary habits of an extensive and representative sample within a given context allows the identification of foods that most significantly convey impacts, indirectly incorporating the nutritional variable. This approach assumes that diets are balanced within a certain range. Therefore, the results will be reported based on the daily impacts of an individual's diet (FU), mediated by annual consumption.

2.2. *Life cycle inventory*

The study analyzed eating patterns in the Italian population using data from the third Italian National Food Consumption Survey (INRAN-SCAI, 2005–2006) run by the INRAN-SCAI Study Group (Leclercq et al., 2009). It represents the most updated data available for the Italian market at the time current date. The survey was conducted on a random sample of 3323 individuals, (1501 males and 1822 females) aged 0.1–97.7 years: 52 infants (0–2.9 years) (2%), 193 children (3–9.9 years) (6%), 247 teenagers (10–17.9 years) (7%), 2313 adults (18–64.9 years) (70%) and 518 elderly (65 years and above) (15%). The adult fraction represents 85% of the sample (2313 adults and 518 elderly). The remaining fraction was composed of younger participants. Participants recorded their food and drink consumption in a 3-day diary. The Italian food items were categorized into 14 major groups and 56 subgroups of foods and beverages, following the classification of the European Food Safety Authority (EFSA, 2005). The amount of consumed food was drawn from data sources (Piccinelli et al., 2011a, 2011b). The regional variability detected served as the basis for formulating five distinct territorial diets (also called macro-regions or clusters): ITALY (national average), NORTH-W (Lombardy, Piedmont, Liguria), NORTH-E (Veneto, Emilia-Romagna), CENTER (Tuscany, Lazio, Umbria), and SOUTH-I (Abruzzo, Molise, Puglia, Campania, Sicily) (Fig. 2a). The remaining regions (Valle d'Aosta, Trentino-Alto Adige, Friuli-Venezia Giulia, Marche, Basilicata, Calabria, and Sardinia) were not included in the published survey.

Data referred to the various inputs and outputs involved in the system boundaries of the various food typologies were drawn by AGRIBALYSE® 3.1 (Colomb et al., 2015) database, using the SimaPro software v. 9.5 (PRé Consultants, 2022). Since information related to the origin of the food consumed in Italy was not available, technologies reported in the AGRIBALYSE® database were adopted for the case study, assuming that the French context could be comparable with the Italian one.

263 food typologies were analyzed. In this study, food typology refers to items consisting of a single food (e.g. *orange*) or a combination of several similar ones (e.g. *various types of cereals*, *fresh egg pasta*, *dry biscuits*, *fruit yogurt*, *various spices*, etc) assembled into 56 subgroups and 14 groups, the latter encompassing all the subgroups and representing the primary focus of this study's evaluation (a simplified representation is reported below in Fig. 2b).

Each tipology was assigned to the respective subgroup, according to (Leclercq et al., 2009). Some foods have been classified according to the group of the main ingredient (e.g., biscuits, pizza with tomato, cereals, etc.); while the majority of foods were disaggregated into their main ingredients. Most Italian recipes, such as lasagna, were analyzed according to the specific amounts of the ingredients comprising it: i.e., meat, tomato sauce, fresh pasta, cheese, etc. The selection procedure of the AGRIBALYSE® proxy to each food typology, including sources and corresponding assignments is reported in ESI (Table S1) to ensure transparency and clarity in the methodology.

An exception was made for some products composed of a main ingredient belonging to one food group and other minor ingredients belonging to different food groups. For instance, the food *Fish sticks* are categorized under the food typology *Cod* and the group *Fish, seafood, fresh, and frozen* even though they contain breadcrumbs. Additionally, a certain number of food products listed in the *Cereals and Derivatives* group contain not only cereals but also other ingredients such as eggs and fats, such as biscuits, baked goods, sweets, sweet snacks, etc. A practical example is represented by the typology Fruit tarts/Fruit pies classified in the group *Cereals and Derivatives*, sub typology *Sweets, and sweet snacks*. This approach allows for the consideration of the complexity of some food products and their differences in classification.

After assigning each of the 263 typologies to its corresponding

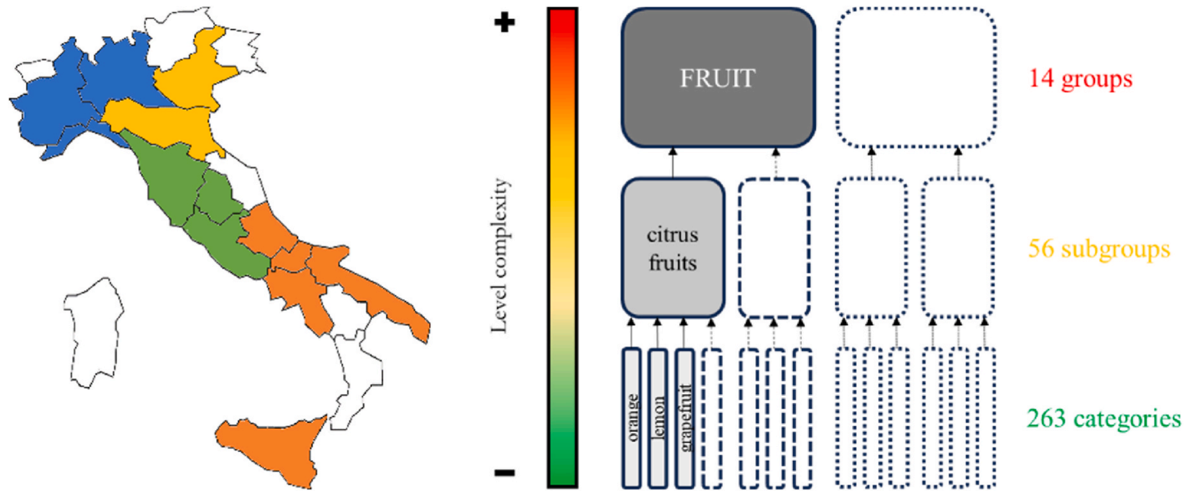

Fig. 2. a) The map highlights the Italian regions surveyed, color-coded by macro-region: NORTH-W (blue), NORTH-E (yellow), CENTER (green), and SOUTH-I (orange). Regions not included in the survey are white; b) Simplified representation of the study domain, with examples of food typologies, subgroups, and groups.

database process, the subgroups were modelled by inputting the processes of the typologies within them. Each new process was modelled for 1 kg of product. Each typology contributes to the total in an amount equal to the ratio between the consumed quantity of that typology (g/day) and the total consumption for that specific subgroup (g/day), **Eq. (1)**.

$$\frac{food\,typology\,(g/day)}{total\,subgroup\,(g/day)} = relative\,contribution\,of\,the\,typology\,to\,each\,subgroup$$

Eq. (1): Contribution of each typology to each subgroup.

56 subgroups were created cumulatively, and the environmental impacts were then calculated for each one of them.

2.3. Life Cycle Impact Assessment

The ReCiPe 2016 Midpoint (H) method (v. 1.08) (Huijbregts et al., 2017), was selected to estimate the potential environmental burdens. Impacts were calculated for all the 18 impact categories. The choice is made in consistency with ISO 14044 and previous studies (ISO, 2006a,b; Cespi et al., 2016), which established that a single-issue evaluation (e.g., solely based on carbon footprint) is not appropriate in LCA, since the chosen impact categories shall reflect a comprehensive set of environmental issues related to the product system under investigation. Despite this, among the whole list of categories proposed by multiple-issue methods, namely: GWP, Global warming (kg CO_2 eq); ODP, Stratospheric ozone depletion (kg CFC11 eq); IRP, Ionizing radiation (kBq Co-60 eq); HOFP, Ozone formation-human health (kg NOx eq); PMFP, Fine particulate matter formation (kg PM 2.5 eq); EOFP, Ozone formation Terrestrial ecosystems kg NOx eq); TAP, Terrestrial acidification (kg SO_2 eq); FEP, Freshwater eutrophic. (kg P eq); MEP, Marine eutrophic. (kg N eq); TETP, Terrestrial ecotoxicity (kg 1,4-DCB eq); FETP, Freshwater ecotoxicity (kg 1,4-DCB eq); METP, Marine ecotoxicity (kg 1, 4-DCB eq); HTPc, Human carcinogenic toxicity (kg 1,4-DCB eq); HTPnc, Human non-carcinogenic toxicity (kg 1,4-DCB eq); LOP, Land use occupation (m^2a crop eq); SOP, Mineral resource scarcity (kg Cu eq); FFP, Fossil resource scarcity (kg oil eq); WCP, Water consumption (m^3); GWP, LOP, WCP have been evaluated with particular attention in the literature (Jones et al., 2016; Nelson et al., 2016) but recently also air and water quality (i.e., eutrophication and toxicity) have received increasing attention (Ivanova et al., 2016; Poore and Nemecek, 2018; Balasubramanian et al., 2021), In the first case, the reason was the notable contribution of the food sector to the global freshwater eutrophication potential, estimated at 78% by Poore and Nemecek (2018). One of the factors responsible for these impacts is the reckless use of pesticides (Nordborg et al., 2017a; 2017b). The impact associated with PMFP was instead considered relevant due to the high influence observed for some food families, such as fish (Arfelli et al., 2024a; 2024b). However, to simplify the communication, only five impact categories were selected for the graphic visualization, based on their particular relevance and significance in the context of the study: GWP, PMFP, FETP, LOP and WCP. Five tables were created (ITALY, NORTH-W, NORTH-E, CENTRAL, SOUTH-I), in which the columns represent the impact categories selected and the rows contain the sub- and food groups. Each cell reports the impact values per each one of them, based on the quantity consumed, expressed in the unit of measurement of the impact category relating to the calculation. Then, an LCIA model was created for all the 14 main groups, including all the subgroups corresponding to each of them. These LCIA models were used to calculate the potential impacts on the selected environmental category related to each food group about the amount consumed.

2.4. Uncertainty analysis

To check the model's robustness an uncertainty analysis was performed. The input data utilized to complete the LCI are based on estimated mean values but encompass a range of uncertainty. Uncertainty in LCA studies can arise from diverse factors, such as reliability, sample size about the total population, representativeness of the sample, geographical variability, and technological correlation. The data included in the LCI are associated with specific uncertainties. Therefore, each process created for each subgroup and group (specific to each scenario) was assigned the respective standard deviation value derived from the CREA database (Piccinelli et al., 2011a, 2011b). The present study used Monte Carlo analysis as the method for the uncertainty assessment, a technique based on random sampling calculation able to repeat the analysis for a higher number of iterations and to estimate the probability distribution of the result (Heijungs, 2020). In our study, the Monte Carlo simulation was applied by considering 1000 runs and a confidence interval of 95%.

3. Results and discussion

3.1. Consumption habits

Fig. 3 shows the adult average daily food consumption per category in the five clusters. The daily food consumption pattern is characterized by a high contribution of cereals and baking products (22% of the total excluding water and drinks), followed by vegetables (18%), fruit (17%),

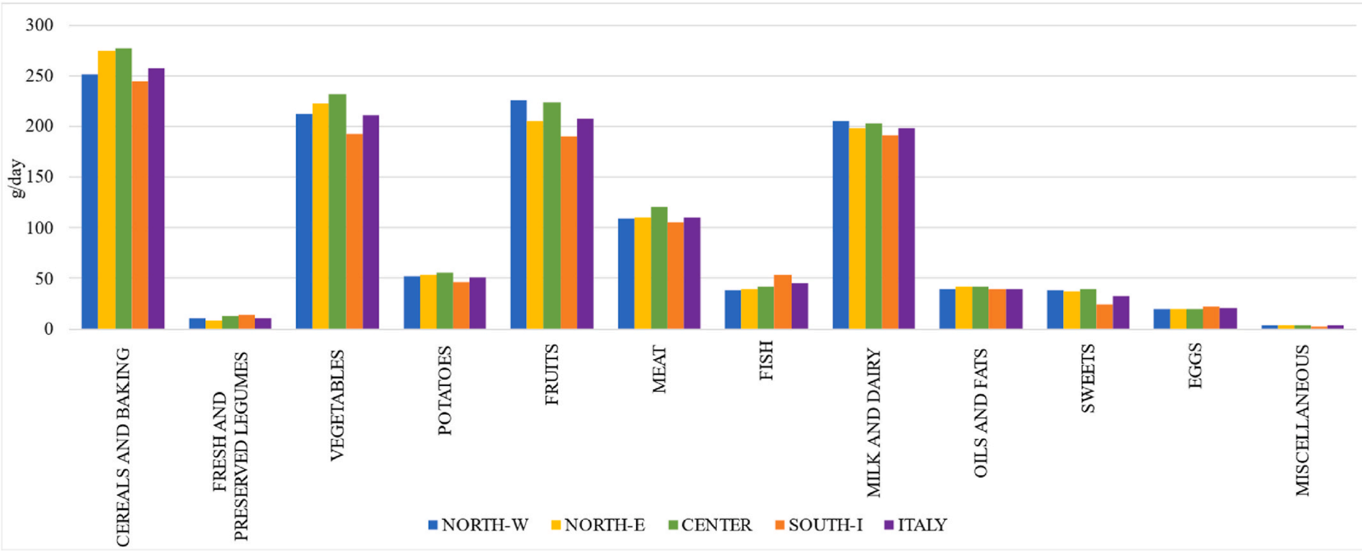

Fig. 3. Average daily food consumption per tipology of adult males and females in the five clusters ITALY, NORTH-W, NORTH-E, CENTRAL, and SOUTH-I.

milk, and dairy (17%). The consumption of meat is relatively high (9%), while the consumption of legumes (1%), fish (4%), and eggs (2%) is significantly lower in the different dietary patterns. Daily consumption of potatoes, oils and fats, sweets, and various products is significantly lower than the other food groups. The water, alcoholic, and non-alcoholic beverage consumption amounts groups are not shown in Fig. 3 to optimize the visualization, since they exceed those of other food groups. The whole set of information is reported in Table S3.

Food consumption data shows similar patterns among the macro-regions, although there is a tendency for lower daily food consumption in the SOUTH-I area, making exceptions for fish and egg groups. This suggests that while overall patterns of food consumption are similar, there are regional variations in the consumption of specific food products, and as a result, there will be different environmental impacts based on dietary patterns. Table S2 shows the LCIA results for each consumption scenario and each impact category analyzed.

Literature demonstrated that the environmental impact of a diet can be significantly decreased by reducing the presence of meat (Arfelli et al., 2024a; 2024b; Masino et al., 2023; Steinitz et al., 2024).

3.2. Life Cycle Impact Assessment

Fig. 4 shows the specific impacts of the five territorial diets per each impact category analyzed and the contribution of the different food products listed in Table S4. The uncertainty analysis results are reported in Table S5 and Fig. S9.

The overall comparison among the 18 categories showed than higher impact of the CENTER macro-region diet, mainly due to the higher amount of consumed food. The contribution analysis confirms that the MEAT group consistently exhibits the highest environmental burden across nearly all impact categories in line with the literature findings (Castellani et al., 2017; Kim et al., 2020). Among the different types of MEAT considered in the study, BEEF was demonstrated to dominate the burdens for the majority of the environmental categories analyzed.

3.2.1. Global Warming Potential

The GWP value estimated for the average Italian diet (Fig. 4a) is 3.4 kg/CO_2-eq. MEAT represented the main GWP contributor (49.8% of the total) and it is followed by the MILK AND DAIRY group (14.9%). Among the regional clusters, CENTER achieves the highest impact (3.7 kg CO_2 eq/FU), followed by NORTH-W (3.6 kg CO_2 eq/FU), NORTH-E (3.4 kg CO_2 eq/FU), and SOUTH-I (3.1 kg CO_2 eq/FU). Regarding MEAT, the GWP impacts are mainly due to beef (31%), pig (4%), and poultry (4%).

Concerning the impact of the average daily meat consumption in Italy (110 g/day), BEEF contributes to 62% of GWP, 50% of PMFP, 37% of FETP, 60% of LOP, while poultry, pork, and other types of meat contribute in smaller percentages. The daily average meat intake in Italy includes 43 g/day of beef (39% of MEAT), 13 g/day of pork (12%), 21 g/day of poultry (19%), and 33 g/day of other types of meat (30%).

3.2.2. Particulate Matter Formation Potential

A similar trend to GWP is observed for the PMFP category (Fig. 4b): CENTER shows the worst score (6.0E-03 kg $PM_{2.5}$ eq/FU), followed by the NORTH-W (5.7E-03 kg $PM_{2.5}$ eq/FU), the NORTH-E (5.6E-03 kg $PM_{2.5}$ eq/FU) and finally SOUTH-I (5.3E-03 kg $PM_{2.5}$ eq/FU). Among the clusters, only the value of SOUTH-I is below the average Italian score. Once again, MEAT represents the most impacting food group (40.8% of Italian PMFP, with 2.3E-03 kg $PM_{2.5}$ eq/FU), followed by FISH (14.1% with 7.8E-04 kg $PM_{2.5}$ eq/FU) and MILK AND DAIRY (10.0% with 5.6E-04 kg $PM_{2.5}$ eq). Concerning PMFP, the MEAT group, particularly beef, negatively affects air quality through direct emissions from intensive animal breeding and agriculture practices (for feed production). The fishing industry is also among the major contributors to air pollution. Boats and ships powered by diesel engines release nitrogen oxides (NO_x) and other pollutants (PM, SO_x, etc.), contributing significantly to damage to ecosystems and health risks. Despite fish consumption in the SOUTH-I scenario being the highest compared to other macro-regions, this contribution did not significantly influence the cumulative impact on this category (less than 18%).

3.2.3. Freshwater ecotoxicity

The FETP for the daily food consumption of an average Italian is 5.8E-02 kg 1,4-DCB/FU, with the most important contribution (Fig. 4c) of the MEAT group, equal to 26% (1.5E-02 kg 1,4-DCB/FU), while DRINKS follow with a contribution of 20% (1.1E-02 kg 1,4-DCB/FU) and CEREALS AND BAKING with 14 % (8.2E-03 kg 1,4-DCB/FU). Compared to the overall impacts of consumption of the macro-regions, the CENTER scenario showed again the highest score, with 6.3E-02 kg 1,4-DCB/FU, followed by NORTH-W (6.2E-02 kg 1,4-DCB/FU), NORTH-E (6.2E-02 kg 1,4-DCB/FU), and last SOUTH-I (5.2E-02 kg 1,4-DCB/FU). Regarding FETP, the consumption of MEAT stands out again as a significant contributor compared to other food groups. However, notably, pork and poultry products are highlighted for their comparatively larger impacts relative to beef and dairy. This emerges from the database information (Colomb et al., 2015).

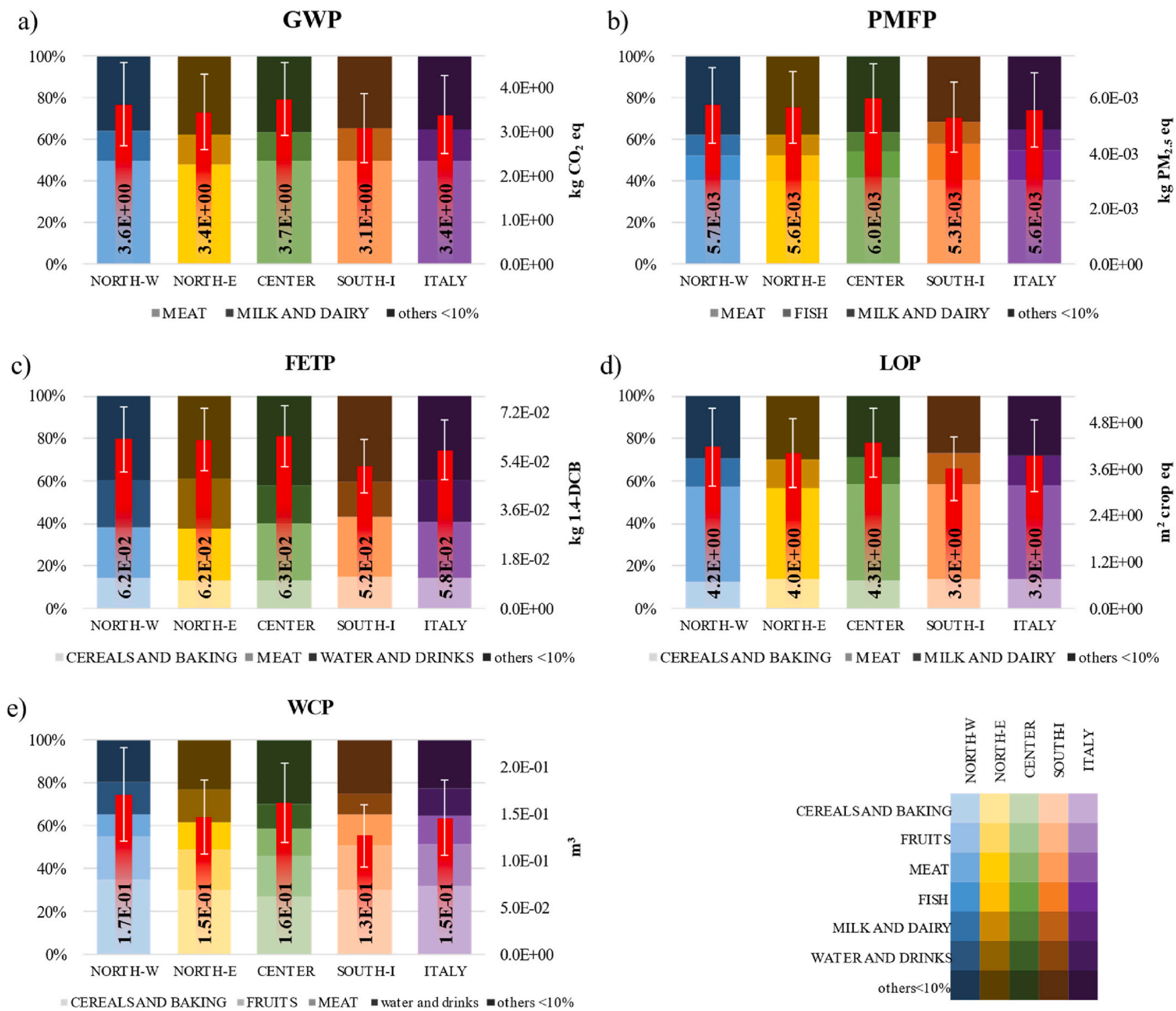

Fig. 4. LCIA percentage contribution of each food group to the total impact of consumption, for each cluster (NORTH-W, NORTH-E, CENTRE, SOUTH-I, ITALY) and impact category selected. "Other <10%" includes food typologies that impact individually for less than 10%. Food groups that contribute more than 10% to at least one impact category are represented by their specific shade (lighter or darker relative to other groups) and colour (depending on the scenario). In contrast, the "Other <10%" group consistently uses the darkest shade. GWP = Global Warming Potential; PMFP = Particulate Matter Formation Potential; FETP = Freshwater Ecotoxicity Potential; LOP = Land Occupation Potential; WCP = Water Consumption Potential. Error bars plotting uncertainty ranges are included. Method: Recanati et al., 2018 Midpoint (H), V1.08.

3.2.4. *Land use occupation*

Even in the LOP category, the CENTER scenario reflects the highest impacts (4.3 m^2 crop eq/FU), followed by NORTH-W (4.2 m^2 crop eq/FU), NORTH-E (4.0 m^2 crop eq/FU), and SOUTH-I (3.6 m^2 crop eq/FU) (Fig. 4d) and +10% concerning the average Italian one (3.9 m^2 crop eq/FU) (41%). This is followed by the MILK AND DAIRY group with 13.7% (5.4E-01 m^2 crop eq/FU) and the CEREALS group with 13% (5.3E-01 m^2 crop eq/FU).

3.2.5. *Water consumption*

Finally, in the case of WCP (Fig. 4e), the NORTH-W scenario reached the highest values, equal to 1.7E-01 m^3/FU, followed by CENTER (1.6E-01 m^3/FU), NORTH-E (1.5E-01 m^3/FU), and SOUTH-I (1.3E-01 m^3/FU). The CEREAL AND BAKING, FRUIT, and MEAT groups emerge as the main contributors to the total WCP in ITALY (1.5E-01 m3/FU), accounting for 31% (4.7E-02 m^3/FU), 19% (2.8E-02 m^3/FU), and 13% (1.9E-02 m^3/FU) respectively. This trend can be attributed to the direct consumption during irrigation and the abundance requirements for grains (Colomb et al., 2015).

3.2.6. *Remaining categories*

MEAT was demonstrated to be the main hotspot for the majority of the remaining category, specifically, on a national level, it contributes 51.4% in ODP, 43.8% in IRP, 50.3% in TAC, 33.1% in MEP; 27.9% in METP; 30.9% in HTPc; 33.7% in SOD; and 30.1% in FFP. More details are reported in Table S6 of the ESI. Exceptions are found in CEREALS AND BAKING, which represents 49.5% of the HTPnc impacts; FISH, which is the main hotspot in HOFP and EOFP (30.9% and 30.5%, respectively) because of the activity of diesel engines in ships in the case of the fished food or the farming phase; ALCOHOLIC DRINKS, which contributes for 59.5% in TETP due to the cereals cultivation phases (i.e., barley in the case of beer) and WATER AND OTHER NON-ALCOHOLIC

DRINKS, which contributes the 30.0% in FEP due to both the influence of beverages components and packaging.

4. Discussion

The GWP value estimated for the average Italian diet (i.e., 3.4 kg/ CO_2-eq) confirms previous literature findings (Ferrari et al., 2020). It is specified that the consumption habits are very representative of the analyzed context (i.e., Italy or specific macro-region), but not necessarily of the global one. Worldwide, the most consumed meat is pork (36%), followed by poultry (33%) and beef (24%) (OECD, 2022). However, since the hotspot of the meat life cycle resulted in the farming phase, confirming a trend that is already well-known in literature, the suggestion of mitigating the GWP impact by reducing MEAT (beef, in particular) consumption, could be extended to a wider spatial and temporal context, assuming that farming phase is dependent on variables which do not directly reflect information which changes in relationship to geographical aspects (e.g., electricity mix). Accordingly, the recommendation regarding the reduction of beef consumption should be considered limited to the Italian context or, at most, the Western context, but it may be valid for other global regions also.

PMFP is confirmed to predominantly depend on animal breeding and agriculture practices associated with food production, in the case of MEAT food typology and on fishing and transportation procedures in the case of fish (Ruiz-Salmón et al., 2021a).

The results observed for FETP, especially regarding pork and poultry are in line with the literature findings (Nordborg et al., 2017a; 2017b). In particular, the discrepancy highlighting a higher influence of pork and poultry instead of beef and lamb is attributed to the extensive use of pesticides, some of which possess high toxicity levels, in soybean production, a key component of animal feed (Wang et al., 2024; Henry et al., 2011; Nordborg et al., 2017a; 2017b). The issues related to toxicity in certain stages of the food chain are primarily attributed to heavy metals involved in pesticide use (Kumar et al., 2019).

Regarding the LOP, the significant relevance of MEAT (i.e., 44% of the total diet in Italy) is in line with the findings of Kim et al. (2020) who already identified it as the main contributor to occidental diets. In general, the findings confirm what has been found in literature, highlighting the differences in LOP even with the same food typology: beef or mutton required land per kg of products up to 100 times larger than cereals, while poultry and pork, for example, have a LOP 18–25 times smaller than that of beef per kilogram of food produced (Poore and Nemecek, 2018; Ritchie and Roser, 2019). Such values may be even increased in case animal feeding is produced through organic practices, due to the lower crop yield (Boschiero et al., 2023).

Concerning the results obtained for the WCP category, agriculture emerges as the primary consumer of freshwater globally, accounting for 92% of total consumption (Mekonnen and Hoekstra, 2012) and, according to literature (Mekonnen and Hoekstra, 2011), within agriculture, cereals account for the largest share of water consumption. This is in line with our findings which estimated that the water involved in grain production is 31% of the total. However, compared to animal-based foods, fruit and vegetable production typically requires less water per amount of product (Gibin et al., 2022; Poore and Nemecek, 2018; Capone et al., 2013; Vanham et al., 2013). In general, these findings, accompanied by our results, underscore the significance of evaluating water consumption relative to the quantity of each food consumed, rather than focusing solely on the product itself when assessing the environmental impacts of dietary choices.

To summarize, it is reiterated that the obtained results are confined to the spatial and temporal boundaries of the study and can be extended to broader contexts only if the impacts observed are not dependent on the site-specificity of the inventory. Furthermore, predictions regarding future impacts depend on various factors that are difficult to foresee, ranging from changes in habits to geopolitical events or situations that indirectly influence the food supply chain. In (Chai et al., 2024), the example is given of how unpredictable events, such as wars, can alter the impacts on LOP and biodiversity of a territory. In this context, Chai and colleagues found that such extensions of the land surface required to produce food could be mitigated by the reduction of consumption of red meat, which is responsible for consistent land occupation and also because of the cultivation of animal feed. Consistently, consumer sensitivity on the topic could be useful to reduce the impacts of food even in the case of the presence of unpredictable events.

In addition to these aspects, it is mentioned the importance of considering the nexus between water availability and the food sector (Wu et al., 2024; Campana et al., 2022; Di Martino et al., 2023). In particular, concerning meat, water utilization within the livestock industry extends beyond direct consumption for hydration to encompass a range of auxiliary functions and product processing (e.g., energy), as well as the crucial need for water in feed crop growth (Ran et al., 2016). This statement reflects the importance of extending the nexus evaluation not only to the food sector but also to energy (Arfelli et al., 2022; Wu et al., 2024), land (Rodrigues de Abreu and Machado, 2023) and mineral and metal ore availability (Font Vivanco et al., 2018).

4.1. Main outcomes, limitations, and future perspectives

The results for the MEAT group suggest the need to consider specific actions to mitigate the environmental impacts. One example could be promoting a reduction in consumption, especially high-impact varieties (e.g., beef and lamb), by replacing them with lower-impact alternatives (e.g., chicken or plant-based diet). A complementary action or an alternative to reducing high-impacting food intake is reducing the consumption of processed foods, which generally exhibit a higher environmental impact compared to less-treated ones (Ruiz-Salmón et al., 2021a; Verbeek et al., 2023). The reduction of processed food consumption might also have benefits for consumers' health (Sinha et al., 2021; Domingo and Nadal, 2016).

The study conducted by Tukker et al. (2011) on European food consumption, suggests that moderate dietary changes are not sufficient to significantly reduce the impact of food consumption. Several authors suggest that the environmental sustainability of food consumption requires more drastic dietary changes (Heller et al., 2013; Garnett et al., 2014; Rancilio et al., 2022). As a first option, the reduction of overall food intake could be considered: an LCA analysis conducted by Franco et al. (2022) highlights how overnutrition has a significant environmental impact in Italy, arguing that the consumption of food that exceeds a balanced caloric intake must be considered a form of food waste, requiring more in-depth knowledge of its environmental implications. A second option, focused on a more drastic reduction in the consumption of food products with a high environmental impact, could be more effective. According to Baroni et al. (2007) carefully crafted omnivorous, vegetarian, and vegan diets can reduce the impacts of a normal Italian diet by more than 50%.

Lastly, the consumption scenarios were created to provide a good representation of the Italian context but it is important to interpret the final results cautiously including the main limitations in the discussion. As known, the quality of the LCIA results depends on the data used for modeling. In this case, the dataset detailing Italian dietary behaviors is not updated as of the present date. The utilization of somewhat obsolete data constitutes the principal constraint of the study, as they may not faithfully represent current consumption patterns. However, the models created for describing the specific case study have a highly flexible structure, allowing for future adaptation to incorporate more up-to-date data, such as from the recent dietary survey in Italy (IV SCAI, 2017–2020; Le Donne et al., 2022; CREA, 2021; CREA, 2022). Unfortunately, during the period of our analysis, the results from the updated survey above were not available for external consultation yet. A further limitation of our analysis is represented by the use of AGRIBALYSE® as a reference database for the LCI stage. It does not fully represent Italian production and consumption patterns. Contextual differences, production methods, and consumption mixes in the AGRIBALYSE® database can significantly influence the results of this LCA analysis. Using inventory data from this database assumes that the food was produced in France, with differences in energy mix for example, contributing to potential result underestimation compared to Italy. Therefore, the study calls for the development of a representative Italian LCI database to improve data quality and accuracy in future assessments. Creating a representative dataset for Italian food production, incorporating local products and common purchases, would improve the study's reliability by avoiding average European data. The forthcoming national open-source LCI databases focused on Italian agri-food production and expected from the ILCIDAF (Italian LCI Database of Agri-Food Products) (Notarnicola et al., 2022) and the Arcadia (in Italian Approccio ciclo di vita nei contratti pubblici e banca dati italiana LCA per l'uso efficiente delle risorse) projects offering potential enhancements for this study. In addition to the site-specificity issue, databases should more accurately clarify the inventories of biological operations with targeted studies aimed at understanding the effective impacts of these practices (Zingale et al., 2022).

The proposed perspective (i.e., comprehensive dietary impacts per macro-area) can be beneficial from a communicative standpoint and might empower the consumer to improve their habits by placing them within a defined context and leveraging on their sense of belonging (Ma and Liu, 2023; Sorkun, 2018). In terms of sustainability, it may be advantageous in the future to extend the assessment to include social variables, thereby guiding consumers towards more informed choices that consider not only environmental factors (Mancini et al., 2023). Key areas for further research include the selection of an appropriate functional unit able to consider nutritional properties, Furthermore, if site-specific data are important during inventory, they may also be crucial during impact assessment for certain environmental categories (e.g., PMFP, LOP, FETP, WCP, etc). Therefore, the adoption of regionalized LCIA methodologies is encouraged.

5. Conclusions

The study utilizes a public collection of data related to consumption habits in the Italian territory to identify hotspots of environmental impact related to *i)* macro-areas or *ii)* food typologies, with the final aim of suggesting changes that can yield maximum benefits to the environment. Regarding macro-areas, the central Italy region emerges as the most impactful in terms of environmental impacts, followed by the north and finally the south. It is not possible to determine whether these differences are conditioned by the data collection system, which in some areas such as the south has proven to be less efficient. Concerning food typologies, in line with the majority of literature in the field, MEAT emerges as the main hotspot, dominated by beef. For example, the MEAT impact in terms of GWP is notable, with a significantly higher percentage (50%) compared to the other groups, also in PMFP, FETP, and LOP (41%; 26%; 44% respectively).

However, it is important to note that this trend did not occur in WCP, where MEAT was not the primary contributor. Instead, MEAT ranked third at 13%, following the CEREAL AND BAKING group at 31% and the FRUIT group at 19%. The differences in impact between food typologies provide a more detailed and nuanced picture of their respective environmental influences. These results emphasize the need to reduce the presence of meat in diets while also considering the impacts of substitutes, which in large quantities can equally contribute significantly to the overall impact of our diet, underscoring the importance of a comprehensive and detailed assessment to fully understand the environmental impact of our dietary choices. These results emphasize the need to reduce the presence of meat in diets. It is suggested to adopt a "macro-area diet" perspective to raise awareness and accountability among consumers in the face of a global need through increased awareness of the territory. The results of the study serve as a starting point for future investigations in the field of environmental assessment of Italian diets.

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CRediT authorship contribution statement

Gaia Mattarello: Writing – original draft, Formal analysis, Data curation. **Francesco Arfelli:** Writing – review & editing, Supervision, Conceptualization. **Daniele Cespi:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Fabrizio Passarini:** Supervision. **Ivano Vassura:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.119867.

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