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The MED_EAT-IT approach: A modelling study to develop feasible, sustainable and nutritionally targeted dietary patterns based on the Planetary health diet

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ABSTRACT

In 2019, the EAT-Lancet Commission introduced the Planetary Health Diet (PHD), a guide for creating 2500 kcal/day country-specific sustainable diets that promote health while reducing the environmental impact associated with food systems. The PHD was previously adapted to the Italian food context, resulting in the EAT-IT dietary pattern. However, this adaptation revealed several challenges in terms of nutritional adequacy, feasibility, and environmental impact. This study reports on strategies to improve the previous pattern and align it more closely with the Mediterranean Diet, resulting in the MED_EAT-IT pattern. The study also explores feasible strategies for adapting this pattern to different energy targets, enhancing its scalability and promoting personalized approaches. For the optimization of this pattern, a specific calculation tool was developed to introduce variation to the pattern, considering realistic and feasible serving sizes and frequency of consumption. This tool integrates a defined food ontology, food composition data, and two environmental impact metrics (Carbon and Water Footprint). To optimize nutritional adequacy, several adaptations of the amount within the different food groups were made, for instance by increasing cereals and animal source by 25.5% kcal/day and 36.2% kcal/day respectively compared to EAT-IT. The resulting 2500 kcal/die pattern meets all nutritional requirements except for vitamin D and does not hamper the possibility to limit environmental impact (Carbon Footprint increased only by 12.2% but Water Footprint decreased by 6.3%). Lower energy targets were achieved by modulating amounts of the different food groups to ensure nutritional adequacy. The strategies and tools proposed here could aid in optimizing dietary plans, evaluating their potential for environmental impact reduction, and identifying issues that could hinder their adoption. Furthermore, the analyses carried out pave the way for the potential future development of new or improved foods that may contribute to the optimization of nutritional and environmental impact of diets.

1. Introduction

Food systems embrace the entire range of actors involved in the production, processing, distribution, consumption, and disposal (loss or waste) of food products originating from agriculture (including livestock), forestry, fisheries, and food industries, along with the broader economic, societal, and physical environments in which these activities are embedded (von Braun et al., 2021). Food systems are currently considered unsustainable due to the large extent of natural resources consumed (e.g., land and freshwater use) and the resulting outputs (e.g., greenhouse gases emission, nitrogen, and phosphorus pollution) against high levels of food waste, the co-existence of malnutrition and overweight/obesity burden, and chronic diseases related to the latter (GBD 2017 Diet Collaborators, 2019; Herforth et al., 2022; FAO, 2022). Despite overall reduction in per capita levels, the environmental impact associated with food systems increased in absolute numbers in the last decades along with food production demands and population growth, urbanization, growing wealth, changing consumption patterns and globalization (Crippa et al., 2021; de Bruin et al., 2021; Dernini and Berry, 2015; Satterthwaite et al., 2010; Sharma et al., 2018; FAO, 2022; Tubiello et al., 2021; White and Gleason, 2022). However, food production will need to further increase, given that the global world

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population reached the number of 8 billion individuals in 2022, and is expected to exceed 9 billion by 2050 (Finley et al., 2017; United Nations Department of Economic and Social Affairs, Population Division, 2022; van Dijk et al., 2021). In this context, enabling future food systems to feed a growing global population without further endangering the state of natural resources, represents a major challenge that involves also shaping healthy and sustainable dietary patterns towards implementation at household and individual level (FAO and WHO, 2019).

In this regard, in 2019 the EAT-Lancet Commission on Healthy Diet from Sustainable Food Systems proposed a scientific approach to foster the adoption of more healthy and sustainable diets (Willett et al., 2019). This proposal involved the calculation of a set of intakes for different food groups (i.e., the EAT–Lancet healthy reference diet - ELHRD, or Planetary health diet - PHD) theoretically consistent with scientific data on healthy diets. However, the novelty of the proposal is related to the fact that this guidance is also consistent with six “scientific targets for food systems” (e.g., a boundary of 4.7–5.4 Gt of CO2 eq. per year to contrast climate change). These scientific targets are based on Planetary Boundaries framework and were established by the Commission to allow the achievement of United Nations Sustainable Development Goals (SDGs) and Paris Agreement (Willett et al., 2019; United Nations, 2021). Briefly, the ELHRD is framed to optimize both health and diet-related environmental impact and should be used at national/regional level to develop country specific healthy and sustainable diet, once adapted to the considered food context. The ELHRD prompted considerable scientific debate since its publication and has been compared to national Food-Based Dietary Guidelines (FBDGs) in USA (Blackstone and Conrad, 2020) and Australia (Hendrie et al., 2022), as well as current diets in India (Sharma et al., 2020), Spain (Cambeses-Franco et al., 2022), and Japan (Nomura et al., 2023). Furthermore, several scores to evaluate adherence were elaborated and validated or used to assess the association with nutritional adequacy, indicators of environmental impact or risk of chronic diseases (Ali et al., 2022; Cacau et al., 2021, 2022; Cacau and Marchioni, 2022; Campirano et al., 2023; Colizzi et al., 2023; Frank et al., 2024; Hanley-Cook et al., 2021; Kesse-Guyot et al., 2021; Knuppel et al., 2019; López et al., 2023; Marchioni et al., 2022; Montejano Vallejo et al., 2022; Stubbendorff et al., 2022; Trijsburg et al., 2021). However, besides the alignment of the current diets or national FBDGs, the report of the Commission did not indicate a standardized methodology to perform the adaptation to the different food contexts (Blackstone and Conrad, 2020). To our knowledge, only few proposals of adaptation were proposed, such as those based on Danish and Italian food context (Lassen et al., 2020; Tucci et al., 2021).

One of the peculiar aspects of the ELHRD is that it was settled on 2500 kcal/day (Willett et al., 2019). This energy target was chosen by the Commission since it is close to the global average per capita energy intake and was considered an adequate target that would fit the higher share of population energy requirements at global level (Willett et al., 2019). However, it should be considered that in developed economies a sizable group of the population present lower energy requirements due to sedentary lifestyles or the need of reducing body weight. In fact, a high body mass index (BMI) represents one of the main risk factors for attributable death and disability, especially in relation to cardiovascular diseases and diabetes (GBD 2019 Risk Factors Collaborators, 2020). Also, different approaches can be selected when defining healthy and sustainable dietary patterns due to the large variety of possible eating behaviors, that conceivably have an impact on the actual chances of adoption of the model sought to be advocated (Biesbroek et al., 2023; Moreno et al., 2022). Given this background, the evaluation of the actual scalability of the ELHRD across different energy targets, thereby improving or resolving current issues related to nutritional adequacy, feasibility, and acceptability, while meeting environmental constraints in the broadest possible way, constitutes an important task that has yet to be tackled.

In 2021 an Italian/Mediterranean adaptation of the ELHRD (the EAT-IT dietary pattern) was developed by our research group with the intention of proposing a model in line with the ELHRD recommendations, but in compliance with Italian eating habits, in terms of number and type of meals (Tucci et al., 2021). This elaboration, targeted to 2500 kcal, was then assessed for potential nutritional issues, and compared with the Italian FBDG. Briefly, calcium, among the others, was found to be a critical nutrient, as the EAT-IT dietary pattern resulted in an amount lower than the Average Requirement (AR) for the adult population (i.e., 800 mg of calcium/day) (Tucci et al., 2021). This pattern was found to be characterized by scarce amounts of dairy and red meat (i.e., beef, lamb, and pork), and a daily intake of legumes and nuts, while their consumption among the Italian population is considerably lower ((EFSA,)EFSA. Food consumption data, updated in 2022). As regard the carbon footprint (CF), the EAT-IT dietary pattern had a lower impact if compared to a model based on Italian FBDGs and to the current consumption of the Italians (Ferrari et al., 2020; Rosi et al., 2017; Tucci et al., 2022). Starting from these considerations, it seems desirable to further optimize the pattern, targeting i) a large segment of the population with lower energy needs and; ii) strategies to achieve increased nutritional adequacy and acceptability.

Based on these premises, the aim of this study was threefold: i) to improve the previously developed EAT-IT dietary pattern to reduce the criticalities observed in term of nutritional adequacy and feasibility also promoting a closer alignment to the Italian/Mediterranean food habits (the MED_EAT-IT dietary pattern); ii) to define strategies of adaptation of the MED_EAT-IT to different energy targets to be used in the context of sustainable personalized diets; iii) to assess the nutritional adequacy and environmental sustainability of the new pattern and derived adaptations.

2. Methods

2.1. Development of the improved and optimized dietary pattern (MED_EAT-IT)

For the shift from the EAT-IT into the MED_EAT-IT dietary pattern, different reforms have been implemented, as reported in Table 1. To enhance feasibility and acceptability, the consumption of legumes was reduced, and the consequent reduction in energy, non-heme iron and fiber was compensated by increasing the amount of fruits and vegetables (lower in the EAT-IT dietary pattern in comparison with recommendation of Italian FBDG) and cereals (considering both wholegrain and refined cereals product), contributing to better alignment of the model to the Mediterranean dietary context (increasing energy from carbohydrates). To reduce the excessive energy from fats and increase feasibility, a reduction in the intakes of daily added fats and nuts was targeted. In addition, butter was separated from the dairy food group and included in “added fats” food group to allow a more truthful elaboration in relation to the Italian food context, since butter is consumed as an alternative to oils and not as a substitute of milk and cheeses. To increase calcium amount, increase in overall dairy category intake was also targeted, considering daily consumption of milk or yogurt, and consumption of 2 portions of cheeses along the week. Also, since water can represent a viable contribution to calcium intake, especially when considering individuals adhering to plant-based diets, the calcium intake deriving from tap water consumption as suggested by Italian FBDG for 2500 kcal (i.e., at least 2000 mL of water/day) was deemed, considering that tap water in Italy can provide up to 98 mg/L of calcium (Italian Ministry of Health, 2016). Finally, an increase of animal food sources other than dairy and red meat (e.g., fish and eggs) was considered as being useful to provide the model with other highly bioavailable micronutrients such as heme iron, zinc, as well as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). An occasional consumption of cured meat mainly from pork (e.g., ham, mortadella, and speck) was also deemed, since these products represent traditional and highly available food products within the Italian food context. However, to compensate for increased levels of environmental impact, a reduction in beef and

Table 1
Targeted variation to shift from the EAT-IT to the MED_EAT-IT, according to previously assessed issues.

Critical issue		Considered variation
Cultural acceptability	Concern about actual acceptability and feasibility due to the very high amount of legumes and nuts in comparison with Italian food habits	Reduction in the intake of nuts and legumes
	Sub-optimal alignment with Mediterranean diet	Increase in the intakes of fruits, vegetables and cereals and derived products
	Butter included within the "dairy" food group, despite being consumed as added fats	Separation of butter from the dairy food group, and inclusion within the more appropriated "added fats" group
Nutritional adequacy	Reduced dietary sources of calcium and difficulties to reach the recommendations	Increase in the intake of dairy. Inclusion of water as contributor to calcium intake, not considered in previous assessments
	Energy from lipids above the recommendations	Reduction in the intakes of added fats and nuts
	Concerns about the actual bioavailability of some micronutrients (e.g., calcium, iron, zinc) due to low amount of animal food sources, and excessive fiber intake	Increase in the intake of animal food sources, with possible reduction in the intake of beef to avoid compensating for the likely increase in environmental impact levels. Avoidance of exclusive consumption of wholegrains cereals to limit intake of fiber that can reduce micronutrients bioavailability (e.g., phytates)

pork consumption was instead taken into account. Italian FBDGs suggest a consumption of red meat (including both beef and pork) of 100 g, 1 time/week, thus leaving room for reduction of these food sub-groups.

2.2. *Development of a calculation tool to assess the nutritional and environmental impact of pattern's modification*

To be able to determine the actual extent of the targeted variations described in section 2.1 above, a calculation tool was also developed within the present study to adapt dietary patterns through the mean energy intake for the different food categories, consistently with ELRHD setup. This tool was structured to allow the management of portion sizes and frequencies of consumptions, in relation to the energy targets defined for each food category. Data from Willett et al. (2019) were used to set the backbone structure of the elaboration, but with the possibility to modulate the mean energy per day associated with the different food groups, sub-groups, and the basket of selected food items to be included for each of them. To allow the estimation of nutrient intake, food composition data were extracted with permission from the Food Composition Database for Epidemiological Studies in Italy (Food Composition Database, 2022), considering all available data on macro and micronutrients. Heme iron was not provided by the database, and thus was estimated as already reported in literature, considering 40% of the total iron from beef, pork, cured meat, chicken and other poultry, and seafood (Monsen et al., 1978). For the estimation of the associated environmental impact, data from the SU-EATABLE LIFE database (Petersson et al., 2021) were used (freely available at https://figshare.com/ndownloader/files/27921765).

From an operational point of view, a food ontology was developed through the hierarchical definition of food groups and sub-groups (e.g., whole milk yogurt data were included within the food sub-group "yogurt" of the food group "dairy"). To account for cultural acceptability, only foods or food products commonly available in the Italian/Mediterranean context were considered for each food sub-group. See Supplementary materials (Table s1) for a clear description of the defined food ontology. Average nutritional composition of each food group/sub-groups is automatically calculated and integrated with data of CF and WF. As recommended by the authors of the SU-EATABLE LIFE database, median data from "typology" level (i.e., aggregated level of food commodity as generally known in the food systems, that represents a group of items having similar characteristics) or "sub-typology" (i.e., further level of aggregation applied to further subdivide typologies with large variability of data) were used (Petersson et al., 2021). Used environmental impact data are outlined in Supplementary materials (Table s2).

Once the food ontology is settled, variation from the original amount suggested by the Planetary Health Diet for the different food groups can be introduced through the modulation of the corresponding mean energy/day. To further account for cultural acceptability, portion sizes are calculated differently from diet optimization studies in which they represent the final output once the different constraints are settled. For a detailed description of the process and the equations used throughout these steps see Supplementary materials, Box s1. Briefly, in this study the developed tool calculates the total weekly or monthly amount that should be consumed to adhere to the pattern according to the mean energy/day of each food group/sub-group. Thus, a frequency of consumption can be settled, and the resulting portion sizes are displayed. To avoid achieving a theoretically optimized pattern, but at the expense of real feasibility, only reasonable portions sizes were considered for this study, according to quantitative standards of portions (see Supplementary materials, Table s3). At this point, the calculation tool provides the corresponding nutritional profile, total environmental impact in terms of CF and WF, and the relative contribution to each nutrient intake and environmental impact metrics of each food group/sub-groups. To account for nutritional adequacy, the nutritional profile is also automatically compared with the Dietary Reference Values for adults (see Supplementary materials, Table s4).

2.3. Adjustment of the MED_EAT-IT dietary pattern to different energy targets

To evaluate the possibilities and related issues of adapting the pattern to different energy targets, the adaptations to 2000 kcal, 1800 kcal and 1600 kcal were explored. These targets were selected considering that they might be applicable in different groups of the Italian population; for instance, while the energy target of 2500 kal/die was in line with the energy needs for individuals with an active lifestyle, the 1800 kcal/die and 2000 kcal/die energy targets could be suitable for sedentary and moderately active subjects, who represents more than 50% of Italian populations (Istituto Superiore di Sanità, www.epicentro.iss.it). The 1600 kcal/die energy target can represent a potential suggested energy intake in people with energy restriction being overweight, who account for about 36% of the Italian adult population ((Istituto Nazionale di Statistica,) www.istat.it). In relation to the considered energy targets, concerns may arise regarding the fulfillment of nutritional requirements (e.g., for micronutrients). However, to achieve these adaptations several approaches could have been used to safeguard nutritional adequacy, since the modulation of food groups do not need to be strictly proportional (e.g., an overall 20% reduction to shift from the 2500 kcal to the 2000 kcal energy target). In fact, a proportional adjustment would represent a theoretical approach that can negatively affect portion sizes' feasibility. Also, a proportional approach would have unavoidably entailed a proportional reduction in the levels of intake for every nutrient and this could be critical for some micronutrients (e.g., calcium would decrease from 1077 mg/day to 862 mg/day), thus exacerbating the nutritional issues previously described. However, the aim of the EAT-Lancet commission was to define practical dietary guidelines to promote adequate nutrition and low environmental impacts, and it has been calculated that this pattern is already within the threshold of safe operating space for environmental impact (Springmann et al., 2020). Thus, any remodulation of portion sizes and frequencies of consumption aimed at lowering the energy target while safeguarding nutritional adequacy can be considered for the adaptation, as long as the overall environmental impact is maintained below the impact associated with the 2500 kcal pattern. For this reason, the variations introduced to remodulate the pattern towards the lower energy targets through the calculation tool involved the maintenance of animal food sources, fruits, and vegetables portions unvaried as much as possible and, when necessary, they were reduced considering frequencies of consumption suggested by Italian FBDG. Legumes, nuts, and oils were instead progressively decreased, while a slight increase of dairy was considered to maintain levels of calcium within recommended levels.

3. Results

3.1. The MED_EAT-IT dietary pattern

A synthesis of the food groups and sub-groups considered for EAT-IT dietary pattern (i.e., the same food groups and related amount suggested by the ELHRD) and the improved MED_EAT-IT pattern is reported in Table 2.

3.2. Calculation tool optimization

The interface of the calculation tool developed on Excel spreadsheets is shown in Fig. 1. This calculation tool allows the development of healthy and sustainable dietary patterns in a straightforward manner. The main methodological differentiation from modeling tools based on the fulfillment of nutritional or environmental constraints lies in the fact that being focused on realistic portions and consumption frequencies allows for the evaluation of more realistic healthy and sustainable dietary patterns. The main panel of the interface only requires the setting of the average daily calories for each food group (whose average energy density per 100 g of food is automatically calculated depending on the foods included for that group) and daily consumption frequencies. The model consequently shows what the resulting portion size would be, thus allowing the evaluation of its feasibility. Once the energy target has been reached, nutritional adequacy and the level of environmental impact can be verified. The tool automatically shows if any intake is outside the nutrient reference values (Dietary Reference Values from Reference Intake Levels of Nutrients and Energy for the Italian population – LARN, and from European Food Safety Authority - EFSA) and shows the contribution in both percentage and absolute terms of each food group and subgroup, considering 86 macro- and micronutrients. It also provides the total CF and WF of the diet, expressed as an average annual absolute value, average daily value or per 1000 kcal. For both nutrient profile and environmental impact, the tool also calculates the contributions of each food group and subgroup.

3.3. The MED_EAT-IT nutritional and environmental profile and possible strategies to address different energy targets

Nutritional profile and indicators of environmental impact for the MED_EAT-IT dietary pattern and its possible adaptations for lower energy targets, obtained using the calculation tool, are reported in Table 3. Considering the 2500 kcal pattern, nutritional adequacy increased significantly, with only Vit. D resulting below LARN average requirements (i.e. 10 μg). Calcium intake increased from 732 mg/day to 1056 mg/day, thus reaching the recommendations of 1000 mg/day for adults with 19% deriving from tap water (2 L/day, providing 100 mg of calcium/L) and 35% from dairy intake. Total iron intake was maintained above the PRI for female subjects (i.e., 18 mg/day), with cereals and vegetables being the main contributors (34% and 22% respectively). Total fiber resulted within the upper value of the reference intake established by LARN (i.e., 16.7 g/1000 kcal), deriving mainly from cereals (38%), fruits (21%), vegetables (20%), legumes (10%) and nuts (7%).

Considering the adaptation to 2000 kcal, added sugars were proportionally reduced with respect to 2500 kcal, from 120 kcal/day to 96 kcal/day. Fats and nuts were decreased from 386 kcal/day to 267 kcal/day and from 195 kcal/day to 160 kcal/day, respectively. Cereals were also reduced from 1018 kcal to 724 kcal. On the contrary, tubers, beef, pork, cured meat, chicken and other poultry, eggs, and seafood were not modified from the amount rescaled in the MED_EAT-IT. Dairies were increased to ensure calcium intake within recommended levels by increasing the portions of milk or yogurt from 200 mL to 250 mL. Fruits and vegetables were slightly decreased compared to the 2500 kcal MED_EAT-IT (from 94 kcal/day to 82 kcal/day) to avoid exceeding the reference intake for fiber. This approach allowed to preserve nutritional adequacy for almost all micronutrients, apart from Vit. D (See Table 3). Total iron decreased to 15.3 mg, and thus above the average requirement (AR) of 10 mg for adult women, but below the PRI of 18 mg. However, estimated heme iron decreased less markedly, and calcium levels remained above 1000 mg. Compared to the 2500 kcal MED_EAT-IT, the environmental impact decreased by 4.7% for CF (from 2.76 to 2.63 kg CO_2 eq./day), but WF decreased by 11.5% (from 3254 to 2880 L/day). Food groups contribution to total CF and WF are reported in Figs. 2 and 3.

To further implement plausible adaptations to lower energy intake (i.e. 1800 and 1600 kcal), cereals and tubers were progressively reduced, up to 575 kcal/day. Legumes, nuts, and added fats were also progressively reduced (up to 44 kcal/day, 128 kcal/day, and 160 kcal/day respectively). Sugars were decreased proportionally to the reduction in energy target (up to 36%). These adaptations also required a slight decrease in some animal food sources, i.e., cured meat, chicken and other poultry and seafood to avoid excessive protein intake, since subjects presenting low energy expenditure are also likely to require less protein intake. Dairy were instead slightly increased to provide adequate calcium intake by adding a weekly portion of fresh cheese (2 portions/week of 125 g of fresh cheese) and maintaining water intake settled to a

Table 2
Food groups and sub-groups differentiation between the EAT-IT and the nutritional optimized MED_EAT-IT pattern.

ELHRD		EAT-IT		MED_EAT-IT		Percentage differences in mean energy/day for different food groups (MED_EAT-IT compared to EAT-IT/ELHRD[a])	Portion sizes examples
Food groups	Food sub-groups	Food groups	Food sub-groups	Food groups	Food sub-groups		
Whole grains	Rice, wheat, corn, and others	Whole grains	Bread, crispbread (melba toast, rusks), pasta, rice, other cereals (barley, spelt, polenta)	Cereals and whole grains[b]	Bread, pasta, rice, other cereals (barley, spelt, polenta), breakfast cereals, crispbread (melba toast, rusks)	↑ 26% (from 811 to 1018 kcal/day)	200 g of bread (4 times/week); 130 g of pasta (4 times/week); 130 g of rice (2 times/week); 130 g of other cereals e.g., "polenta" (2 time/week); 45 g of oat flakes or corn flakes or 6 slices of melba toast 1 time/day
Tubers and starchy vegetables	Potatoes and cassava	Tubers and starchy vegetables	Potatoes	Tubers	Potatoes	↑ 23% (from 39 to 48 kcal/day)	200 g of potatoes (2 times/week)
Vegetables	Dark and green vegetables, red and orange vegetables, other vegetables	Vegetables	Dark and green vegetables, red and orange vegetables, other vegetables	Vegetables	Vegetables rich in carotenoids, vegetables rich in glucosinolates, vegetables rich in polyphenols, other vegetables and mushrooms	↑ 21% (from 78 to 94 kcal/day)	140–250 g/day of different vegetables (2 time/day)
Fruits	All fruits	Fruits	All fruits	Fruits	Fruits rich in carotenoids, fruits rich in polyphenols	↑ 27% (from 126 to 160 kcal/day)	175–180 g of different fruits (2 times/day)
Dairy Foods (Including cheeses and dairy fats)	Whole milk or derivative equivalents (e.g., cheese)	Dairy Foods (Including cheeses and dairy fats)	Whole milk or derivative equivalents (e.g., cheese). Also including butter.	Dairy foods	Milk, yogurt, fresh cheeses, semi-hard and hard cheeses	↑ 18% (from 153 to 181 kcal/day)	200 g of milk or yogurt (1 time/day); fresh cheeses 125 g (1 time/week); semi-hard and hard cheeses 75 g (1 time/week)
Protein sources	Beef and lamb, pork, chicken and other poultry, eggs, fish, legumes, tree nuts	Protein sources	Beef and lamb, pork, chicken and other poultry, eggs, fish, legumes, tree nuts	Protein sources	Beef, pork, cured meat, chicken and other poultry, eggs, seafood, legumes	Beef ↓67% (from 15 to 5 kcal/day)	100 g (1 time/month)
						Pork ↓27% (from 15 to 11 kcal/day)	100 g (2 times/month)
						Cured meat[c] 9 kcal/day	80 g (1 time/month)
						Chicken and other poultry ↔ (62 kcal/day)	170 g (2 times/week)
						Eggs ↑ 116% (from 19 to 41 kcal/day)	2 medium eggs (2 times/week)
						Seafood ↑ 68% (from 40 to 67 kcal/day)	Fish 150 g (2 times/week); crustaceans or mollusk 160-100 g (1 time week)
						Legumes ↓64% (from 284 to 103 kcal/day)	50 g of dried legumes, or 200 g of fresh legumes (4 times week)
				Nuts	All nuts, including peanuts	↓33% (from 291 to 195 kcal/day)	30 g of nuts/day (6 walnuts, 27 almonds, 43 pistachios)
Added fats	Palm oil, unsaturated oils, lard or tallow	Added fats	Extra virgin olive oil	Added fats	Extra virgin olive oil, butter	↓14% (from 450 to 386 kcal/day)	25 g/day of extra virgin olive oil (2 times/day); 12 g of butter (3 times/

(continued on next page)

Table 2 (*continued*)

ELHRD		EAT-IT		MED_EAT-IT		Percentage differences in mean energy/day for different food groups (MED_EAT-IT compared to EAT-IT/ELHRD[a])	Portion sizes examples
Food groups	Food sub-groups	Food groups	Food sub-groups	Food groups	Food sub-groups		
							week), in substitution to oil
Added sugars	All sweeteners	Added sugars	All sweeteners and discretionary foods rich in sugar (e.g., jam, fruit juices)	Discretionary foods and beverages (e.g., jam, fruit juices)	Biscuits, brioche, cakes and bakery products; fruit juices	↔ (120 kcal/day)	30 g of biscuits (3 times/week); 50 g of brioche (2 times/week) or 100 g of cakes and bakery products (1 time/week); 180 mL of fruit juice (1 times/week)
				Water	Tap water and bottled water	2000 mL[c]	10 glasses/day

[a] The EAT-IT dietary pattern used the daily amount suggested by the ELHRD to define a consistent adaption to the Italian food habits, and thus the amount of the EAT-IT dietary pattern are superimposable to the ELHRD, while the MED_EAT-IT represent the willingness to introduce variation in those amounts to tackle the criticalities emerged from the evaluation of the nutritional adequacy of the EAT-IT dietary pattern.

[b] To account for cultural acceptability and reduce phytate levels, bread, pasta, and rice were considered as 50% wholegrain and 50% refined (e.g., 2 portions/week of wholegrain bread, and 2 portions/week of white bread).

[c] Recommendations for cured meat and water were not reported for the ELHRD, thus for these food groups it is reported the amount considered for the current elaboration.

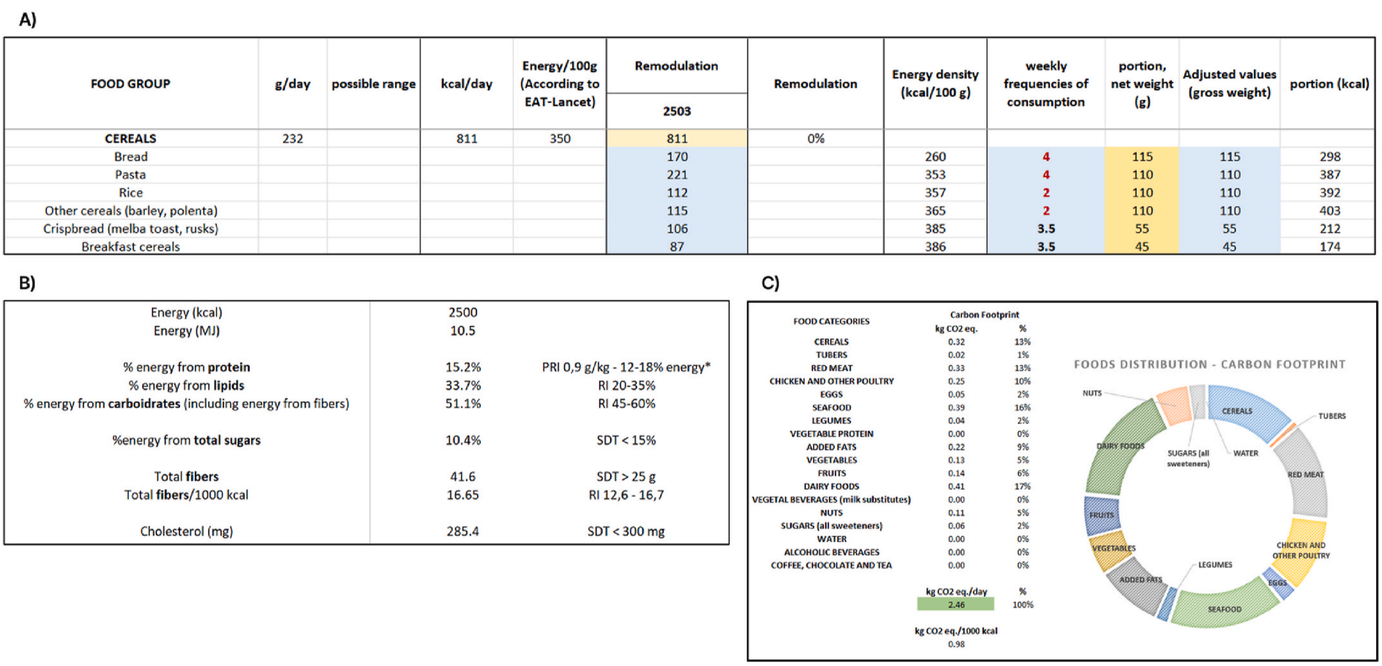

Fig. 1. Overview of the developed tool, used to calculate the effect of qualitative and quantitative food groups variation, considering realistic and feasible dietary patterns. A) interface for processing dietary patterns, B) output: nutritional profile and comparison with reference values, C) output - environmental impact.

minimum of 1800 mL of tap water for the 1600 kcal adaptation.

By considering the nutritional dimension, the adaptation showed increased difficulties in maintaining optimal nutrient adequacy for total iron and zinc, depending mainly on the necessary reduction of cereals to allow the reduction in total energy, fiber and phytates. However, heme iron remained almost preserved due to the modest reduction in animal food sources. Although the percentage of energy from protein and saturated fat gradually increases as energy is decreased (although remaining within the recommendations), the absolute amounts decrease, thus maintaining a correct nutritional adequacy for these two nutrients. Total environmental impact decreased considerably, reaching the lowest value of 2.36 kg CO_2 eq./day for CF, and 2423 L/day for WF for the 1600 kcal adaptation. Food groups contribution to total CF and WF are reported in Figs. 2 and 3.

4. Discussion

This study aimed at exploring strategies and related methodologies to enhance nutritional adequacy, acceptability and scalability of patterns based on the ELRHD, using the Italian context as model. Specifically, the MED_EAT-IT pattern here reported represents an optimized diet, developed through the modification of criticalities we previously assessed (Tucci et al., 2021, 2022). To optimize the pattern, some animal-based foods (e.g., dairy, seafood, and eggs) had to be increased, while other food groups (e.g., red meat, legumes, nuts, and added fats) were decreased. These adjustments allowed to optimize the overall

Table 3
Nutritional and environmental profile of elaborated dietary patterns.

Variable	[a]EAT-IT (2500 kcal)	MED_EAT-IT (2500 kcal)	MED_EAT-IT (2000 kcal)	MED_EAT-IT (1800 kcal)	MED_EAT-IT (1600 kcal)
Energy (kcal – MJ)	2503–10.5	2500–10.5	2000 - 8.4	1800–7.5	1600–6.7
% proteins	14.5	15.2	16.8	17.6	18.0
% lipids	38.3	33.7	33.6	33.0	33.5
% carbohydrates	47.2	51.1	49.6	49.4	48.5
% total sugars	9.2	10.4	12.0	12.4	12.8
Total fiber (g)	43.7	41.6	32.3	30.0	26.6
Total fiber/1000 kcal (g/1000 kcal)	17.5	16.7	16.6	16.6	16.6
% SFA	7.6	8.0	8.6	9.3	9.9
% MUFA	20.7	16.9	15.9	14.8	14.3
% PUFA	6.3	5.3	5.3	5.2	5.2
% ω-6	5.4	4.4	4.3	4.1	4.2
% ω-3	0.9	0.8	0.9	1.0	1.0
EPA + DHA (mg)	465	710	710	710	602
Cholesterol (mg)	195	285	279	222	209
Vit. B12 (μg)	5.6	4.5	7.1	6.8	6.0
Vit. D (μg)	2.5	3.9	3.8	3.5	3.2
Calcium (mg)	729	1056	1001	1004	1004
Iron (mg)	18.9	18.3	15.3	14.0	12.4
Estimated heme iron (mg)	1.1	1.1	1.1	1.1	0.9
Sodium (mg)	1047	1613	1322	1235	1124
Zinc (mg)	14.0	14.1	12.4	11.8	10.6
Total water (mL)	869	3038	2593	2539	2681
CF (kg CO2 eq./day)	2.46	2.76	2.63	2.55	2.36
CF/1000 kcal (kg CO2 eq./1000 kcal/day)	0.98	1.10	1.31	1.42	1.48
WF (L/day)	3473	3254	2880	2653	2423
WF/1000 kcal (L/1000 kcal/day)	1268	1188	1440	1474	1514

[a] Data for the EAT-IT dietary pattern illustrated in this table derive from the re-elaboration of the EAT-IT dietary pattern using the calculation tool, to guarantee correct comparison among the results of the present optimization and to assess their compliance with previously published data. Abbreviations: SFA, Saturated Fatty Acids; MUFA, Monounsaturated Fatty Acids; PUFA, Polyunsaturated Fatty Acids; ω-6, Omega-6 Fatty Acids; ω-3, Omega-3 Fatty Acids; EPA, Eicosapentaenoic Acid; DHA, Docosahexaenoic Acid; Vit. B12, Vitamin B12; Vit. D, Vitamin D; CF, Carbon Footprint; WF, Water Footprint.

nutritional adequacy for all macro- and micronutrients, apart from vitamin D, with very modest effects on estimated environmental impact indicators.

Recently, Beal and co-workers (2023) recognized the need to increase animal food sources in the ELHRD to improve its nutritional adequacy. However, the qualitative and quantitative remodulation suggested by these authors are only partially comparable with the MED_EAT-IT approach. Beal and colleagues calculated that vit. B12, calcium, iron, and zinc of the ELRHD resulted below the AR for adult population (globally harmonized nutrient reference values) and consequently proposed a revised version of the pattern, settled on 2227 kcal, by increasing mainly beef (+400%), eggs (+316%), fish (+163%), pork (+100%), and poultry (+48%). Also, tubers and starchy vegetables were markedly increased (+413%), 100 g/day of refined cereals were included, while whole grains decreased (−63.0%) (Allen et al., 2020; Beal et al., 2023). Similarly to the MED_EAT-IT pattern, legumes and nuts were reduced (−52% and −83.2%, respectively). However, differently from the MED_EAT-IT, no data about the variation in environmental impact parameters were provided by Bael and co-workers (2023). The main difference between these two approaches is related to dairy intake, which were not increased in the work of Beal et al. (2023) and progressively increased in the MED_EAT-IT when considering adaptation to lower energy targets. Milk and dairy represent the primary sources of dietary calcium and, in addition, they are generally associated with neutral or protective effects for several health outcomes and present intermediate levels of environmental impact (Clark et al., 2019; FAO, 2023; Feeney et al., 2021; Tholstrup, 2006; Tunick and Van Hekken, 2015). Thus, it could be more efficient to re-evaluate such a category by considering the overall impact on the environment, the nutritional status and well-being.

Micronutrients adequacy represents a pivotal element of a healthy diet (Bailey et al., 2015). Currently more than 2 billion people across the world suffer from at least one form of micronutrient deficiency with iron, vitamin A, iodine, vitamin B9 and zinc representing the most widespread deficiencies (Bailey et al., 2015; Han et al., 2022; HLPE, 2017). More than one third of the current global population suffer from iron deficiency and related health problems (Han et al., 2022). Zinc deficiency is also reported to be very common worldwide, causing serious alterations in growth and cognitive development during developmental age, as well as impaired immune system function, skin problems, and increased levels of oxidative stress in adults (Prasad, 2013; Wessels et al., 2017). Plant-based diets can be one of the causes of sub-optimal zinc and other mineral intake in case of excessive levels of phytates, fiber and lignin able to affect micronutrients bioavailability (Bailey et al., 2015; Beal et al., 2017; Hawrysz and Woźniacka, 2023). Furthermore, relying on unrefined cereals and other plant-based foods as sources of iron and zinc could be critical in current context of climate change, considering the experimental evidence showing a non-negligible reduction in their content in many important crops (e.g., wheat, barley, rice, potatoes, soy, and peas), due to increased concentration of CO2 in the atmosphere (Blandino et al., 2020; Myers et al., 2014; Smith and Myers, 2018). On the other hand, animal foods can represent important sources of highly bioavailable micronutrients, as recently reaffirmed by FAO (2023). In the current study, we managed to increase the acceptability and nutritional adequacy of the previous EAT-IT dietary pattern through a modest increase in animal products, and a reduction in over-represented plant-based foods, to accomplish all the advantages of plant-based diets and reducing the possible unintended consequences deriving from sub-optimal nutritional adequacy.

The main aim of healthy and sustainable diets is to enable the fulfillment of nutritional needs through the choice of foods associated with low environmental impact. The elaborations presented in this study indicate that a mild increase of selected animal food sources can be associated with only a modest increase in mean daily CF (+12.2%) and a reduction in WF (−6.3%). Also, both these indexes decreased along with reduction in energy targets, although not proportionally to the reduction in energy, since the food groups associated with a high environmental impact were already reduced in the 2500 kcal pattern, leaving little room for improvements within nutritional constraints.

Regardless of the theoretical profile of a healthy and sustainable

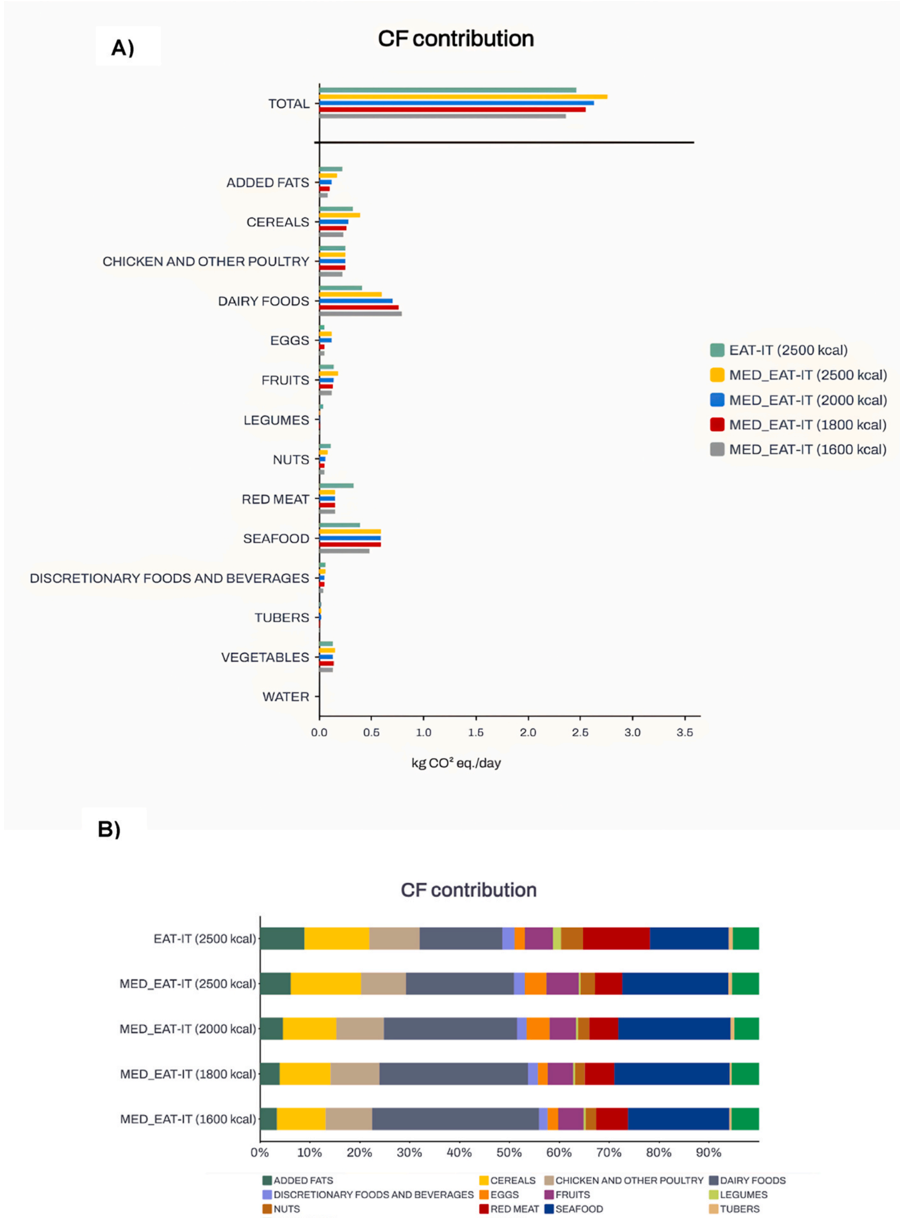

Fig. 2. A) Contribution of single food groups to total CF, expressed in absolute values. Different colors indicate different energy targets adaptations. B) Relative contribution of each food groups according to the different energy targets adaptations. Abbreviations: CF, Carbon Footprint. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

dietary pattern, the benefits of its adoption clearly depend on the characteristics of the habitual diet previously followed. Thus, from a sustainability perspective, reliable data on diet-related environmental impact across the different countries are pivotal to evaluate the actual benefits of the transition towards a sustainable diet. Unfortunately, systematic review collecting harmonized data on diet-related environmental impact across different populations are lacking, and current data are heterogeneous. For example, single studies indicate for the omnivore US adult population a mean CF of 2.23 kg CO2 eq./1000 kcal (O'Malley et al., 2023), for the Brazilian population 2.39 kg CO2 eq./1000 kcal (Garzillo et al., 2021), for the Danish population 2.00 kg CO2 eq./1000 kcal (Trolle et al., 2022), and for the Italian population 1.60 kg CO2 eq./1000 kcal (Rosi et al., 2017). In this study, for the 2500 kcal MED_EAT-IT dietary pattern we calculated a CF of 1.10 kg CO2 eq./1000 kcal, thus corresponding to a reduction of 31.3% of current CF when shifting from a 2500 kcal habitual Italian diet to an isocaloric MED_EAT-IT dietary pattern. These results are in line with a systematic review by Jarmul et al. (2020) who summarized data on the effect of a transition towards healthy and sustainable diets reporting similar percentages of reduction for CF when considering empirical data, thus corroborating the practical approach of the elaboration presented in this work.

The MED_EAT-IT resulted to be associated with lower WF compared to the previous EAT-IT dietary pattern. Average daily WF reported for omnivorous Italian adults was 1271 L/1000 kcal, thus only slightly higher compared to the MED_EAT-IT dietary pattern. Concern regarding the actual sustainability of the ELHRD in terms of water consumption has been already raised, mainly in relation to nut intake (Tucci et al., 2022; Vanham et al., 2020). More recently, a large study used data from the EPIC-NL Cohort to assess the characteristics of highly adherent

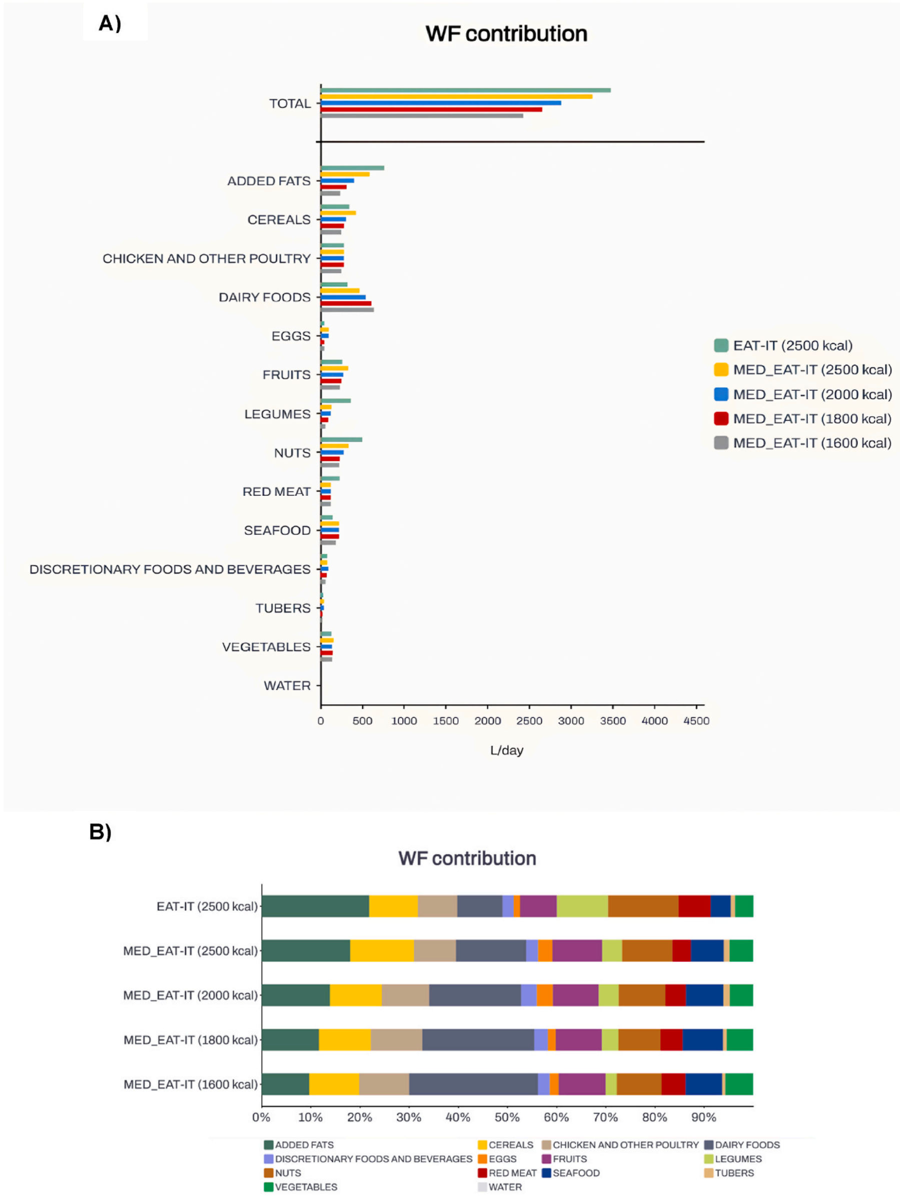

Fig. 3. A) Contribution of single food groups to total WF, expressed in absolute values. Different colors indicate different energy targets adaptations. B) Relative contribution of each food groups according to the different energy targets adaptations. Abbreviations: WF, Water Footprint. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

subjects to the ELHRD vs low adherent subject, analyzing food intake data of 35.496 participants. This study reported that high adhesion to the ELHRD was associated with reduction in multiple environmental impact indicators, apart from blue water use, which instead resulted to be increased (+32.1%) (Colizzi et al., 2023). In this regard, the MED_EAT-IT optimization indicates a neutral effect for water footprint in comparison to habitual Italian diets, thus suggesting that further strategies should be considered to promote WF reduction.

Overall, these data invite a broader reflection considering the global effect of a transition from habitual to more healthy and sustainable diets. Anthropogenic greenhouse gases emissions are fostering current climate change, whose global effects depend on the absolute amount in the atmosphere, independently from the area in which greenhouse gasses are produced and emitted. Current data indicates that Europe currently represents a minor contributor to global greenhouse gas emissions (12.5% in 2021) (Data from Ritchie et al., 2024), with food systems accounting for a third of total greenhouse gas emissions (about 30% in 2015) (Crippa et al., 2021). Thus, a dietary shift across Europe leading to a 31.3% reduction in food system CF would alone translate in an approximately 1.2% reduction of global greenhouse gas emissions. Therefore, the transition towards healthy and sustainable diets should be fostered at global level, combined with other strategies to effectively improve global food system sustainability (e.g., optimization of agricultural practices and resource use efficiency, reduction of food losses and food waste, improvement in foods affordability and accessibility of nourishing foods associated with modest environmental impacts), and mainly involving countries with large potential reductions of environmental impact (FAO, 2010; Kim et al., 2020; Lucas et al., 2023; Marshall et al., 2021; Poore and Nemecek, 2018).

This study also addressed the problem of defining personalized healthy and sustainable diets for different energy targets (from 1600 to 2500 kcal), with a practical approach. Despite a progressive difficulty in maintaining adequate levels of nutritional adequacy, the non-proportional reduction among different foods allowed to maintain heme iron and calcium intake. This is fundamental by considering that often the targets are represented by women (e.g. with an increased iron need with respect to the other population groups or older subjects with special requirements in terms of micronutrients). The definition of healthy and sustainable dietary pattern also for energy targets lower than 2500 kcal can be particularly relevant in dietary contexts characterized by overweight, obesity and diet-related noncommunicable diseases. In 2017, a dedicated group of the Global Burden of Disease Study re-analyzed all reliable data on overweight, reporting that such a condition alone can be considered responsible for almost 40% of deaths from diet-related diseases (GBD 2015 Obesity Collaborators, 2017). On this topic, Zagmutt et al. (2020) questioned that the projected chronic diseases mortality prevention deriving from the adoption of the ELHRD could be achieved by just contrasting overweight. Thus, combining possible benefits deriving from adhesion to balanced healthy and sustainable diets with adequate energy intake could represent a viable strategy to promote health also in developed countries characterized by over consumption.

The identification of potential critical issues in the development and application of healthy and sustainable dietary patterns is of utmost importance to find optimization strategies that can better exploit our traditional food sources, also promoting better nutritional quality and/or reduced environmental impact. At the same time, it can also contribute underlining the eventual actual requirements for new or advanced food products targeted to nutritional and sustainability needs.

5. Limitations

This study presents different limitations, mainly related to the dynamic background in which this analysis was carried out. Despite the definition of a calculation tool specifically designed to elaborate realistic and feasible data, this assessment is still affected by the theoretical approach restrictions that hardly can include all possible variables affecting final scenarios (Mulrooney et al., 2023). Also, data on different food items' environmental impact can be calculated in different ways, depending on multiple factors related to production. Furthermore, environmental impact data can change over time along with technological innovation and resource optimization (e.g., machinery powered by renewable resources, rather than energy derived from fossil fuels). Another limitation is related to the absence of some peculiar and futuristic food choices whose consequences on final health and environmental outcome are currently more difficult to assess, such as the consumption of novel foods (e.g. insects, microalgae, cultured meat), sustainably produced fortified foods or biofortified crops.

Overall, the present and future availability of more significant and reliable data on traditional and new food characteristics (e.g. considering also nutrient bioavailability), environmental impact and actual nutrient needs when considering plant-based alternatives (e.g. throughout the life course or in different physiological/pathological conditions), will be fundamental for the optimization of targeted sustainable diets. In this regard, the developed calculation tool enables the assessment of both the nutritional adequacy and the overall environmental impact of a dietary pattern, also allowing the flexible evaluation of possible substitutions within the different food groups, practically implementing what advocated at theoretical level by the ELHRD in terms of personalization. In this regard, strategies and tools like those proposed here could be helpful for the optimization of dietary plans and for the identification of potential issues.

6. Conclusion

A sustainable food system lies at the heart of the United Nations' Sustainable Development Goals (SDGs). As also specified by the Sustainable Development Goals, the aim of human development is to improve life-quality, health, and longevity. Thus, the definition of sustainable diets cannot simply focus on lowering diet-associated environmental impact but must also aim at the maximization of health outcomes. The ELHRD represents an attempt to define a possible roadmap to achieve improvement in both population health and diet-associated environmental impact. In this regard, the elaboration of the MED_EAT-IT dietary pattern allowed us to assess different nutritional targets also addressing feasibility issues that could reduce its implementation. Furthermore, by considering the presence in the population of a large share of subjects with specific nutritional needs, the availability of possible strategies (e.g., of adaptation and personalization) to meet these requirements seems advisable, rather than a "one size fits all" approach.

CRediT authorship contribution statement

Massimiliano Tucci: Methodology, Investigation, Formal analysis, Writing – original draft. **Daniela Martini:** Conceptualization, Writing – original draft, Supervision. **Valentina Vinelli:** Formal analysis, Writing – review & editing. **Paola Biscotti:** Formal analysis, Writing – review & editing. **Marisa Porrini:** Supervision, review & editing. **Cristian Del Bo':** Investigation, Resources, Writing – review & editing. **Patrizia Riso:** Conceptualization, Writing – review & editing, Supervision, Project administration, All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crfs.2024.100765.

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